Advisory

Onboard Carbon Capture and Storage Review

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List of abbreviations

Abbreviation	Description
ABNJ	Areas Beyond National Jurisdiction
ABS	American Bureau of Shipping
AiP	Approval in Principle
BBNJ	Biodiversity Beyond National Jurisdiction
BECCS	Bioenergy with Carbon Capture and Storage
BIMCO	Baltic and International Maritime Council
BOG	Boil of Gas
BV	Bureau Veritas
$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CCP	Captured Carbon Product
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture, Utilisation and Storage
CEMS	Continuous Emission Monitoring System
CH_4	Methane
CII	Carbon Intensity Indicator
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CR	Capture Rate
CRL	Commercial Readiness Level
DAC	Direct Air Capture
DCS	Data Collection System (IMO)
DEA	Diethanolamine
DNV	Det Norske Veritas
DWT	Deadweight Tonnage
EACCS	Enhanced Onboard Carbon Capture System
EC	European Commission
ECA	Emissions Control Area
EEDI	Energy Efficiency Design Index

EEXI	Energy Efficiency Existing Ship Index
EMSA	European Maritime Safety Agency
EPL	Engine Power Limitation
ETS	Emissions Trading System
ESD	Emergency Shut-Down
EU	European Union
FID	Final Investment Decision
FMEA	Failure Mode & Effects Analysis
FSU	Floating Storage Unit
GFI	Greenhouse Gas Fuel Intensity
GCMD	Global Centre for Maritime Decarbonisation
GHG	Greenhouse Gas
GISIS	Global Integrated Shipping Information System
H_2	Hydrogen
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HFMC	Hollow Fiber Membrane Contactor
HFO	Heavy Fuel Oil
IACS	International Association of Classification Societies
IBC Code	International Bulk Chemical Code
ICS	International Chamber of Shipping
IGC Code	International Gas Carrier Code
IGF Code	International Code of Safety for Ships Using Gases/Low-Flashpoint Fuels
IMDG Code	International Maritime Dangerous Goods Code
IMO	International Maritime Organisation
IPCEI	Important Projects of Common European Interest
ISO Tank	Standardised tank container
LC/LP	London Convention/London Protocol
LCA	Lifecycle Analysis
LCO_2	Liquefied CO_2
LNG	Liquefied Natural Gas
LR	Lloyd's Register
MARAD	U.S. Maritime Administration
MARPOL	International Convention for the Prevention of Pollution from Ships
MEA	Monoethanolamine
MEPC	Marine Environment Protection Committee

MGO	Marine Gas Oil
MGR	Marine Genetic Resource
MMM	Mixed Matrix Membrane
MPA	Marine Protected Area
MR	Medium Range
MRV	Monitoring, Reporting & Verification
MTA	Methanol to Aromatics
MTO	Methanol to Olefins
N/A	Not Available
NaOH	Sodium Hydroxide
Na_2CO_3	Sodium Carbonate
NO_X	Nitrous Oxides
NZF	Net Zero Fuel
NZIA	Net Zero Industry Act
OCC	Onboard Carbon Capture
OCCS	Onboard Carbon Capture and Storage
OCSLA	Outer Continental Shelf Lands Act
OPEX	Operating Expenditure
OSPAR	Oslo-Paris Convention
PCC	Precipitated Calcium Carbonate
PTO	Power Take-Off
PtX	Power-to-X
ROI	Return on Investment
RPB	Rotating Packed Bed
RWGS	Reverse Water Gas Shift
SAF	Sustainable Aviation Fuel
SEEMP	Ship Energy Efficiency Management Plan
ShaPoLi	Shaft Power Limitation
SOLAS	Safety of Life at Sea
SO_x	Sulphur Oxides
STS	Ship-to-Ship
SVPS	Statement of Verified Permanent Storage
TCD	Thermocatalytic Decomposition
TEU	Twenty-foot Equivalent Unit
TRL	Technology Readiness Level
TtW	Tank-to-Wake

UNCLOS	United Nations Convention on the Law of the Sea
USD	US Dollar
VLCC	Very Large Crude Carrier
VLSFO	Very Low Sulphur Fuel Oil
WHR	Waste Heat Recovery
WtT	Well-to-Tank
WtW	Well-to-Wake
ZNZ	Zero/ Near Zero

Executive summary

International shipping faces tightening decarbonisation expectations while alternative fuels scale slowly and unevenly. In this context, onboard carbon capture and storage (OCCS) is one of the few near-term options able to deliver material tank-to-wake reductions on vessels that will continue operating on conventional or transition fuels through the 2030s. The report concludes that OCCS is technically feasible and already demonstrated at sea across multiple ship types and technologies, but commercial diffusion depends on solving three interlocking gaps: ship integration, carbon disposal infrastructure, and regulatory/accounting certainty.

Of the capture families surveyed, amine chemical absorption is the most deployable today (Technology Readiness Level (TRL) ~7–8 at sea), routinely achieving ~70–95% capture rate with high product purity suitable for sequestration or utilisation. Calcium looping offers a solvent-free, safety-advantaged pathway with solid $CaCO_3$ product that aligns well with containerised logistics, while membranes and cryogenic systems are compact or very pure respectively but need more marine validation and careful energy integration. Thermocatalytic Decomposition (TCD)/pre-combustion is promising for LNG carriers and LNG fuelled vessels but remains mid-TRL for shipping. All options impose parasitic energy: typical fuel penalties cluster around ~9–30% for amines, ~15% for membranes, ~10–30% for cryogenics (lower on LNG carriers with cold-energy integration), ~12-15% for thermocatalytic decomposition and ~7–12% for mineralisation, making waste-heat recovery, shaft-generator/PTO sizing, and process integration decisive to economics.

The binding constraint is space/weight/stability, especially the footprint and mass of LCO_2 storage that scales with capture rate and endurance. Above ~50% capture on long routes, LCO_2 tankage can dominate deck real estate on many bulkers and feeders. calcium-looping reduces cryogenics but incurs a 2.27:1 $CaCO_3$:CO_2 mass penalty. Retrofitting often needs deck reinforcement, hazardous-area segregation, and routing redesign. Safety risks are well understood (asphyxiation from CO_2, solvent degradation by-products, cryogenic/overpressure hazards, hydrogen handling on TCD) but manageable with class-approved design, detection/ventilation, and crew training. Offloading is an emerging bottleneck: The LCO_2 conditions on the ship must closely match the required intake conditions of the receiving port facility, vapour return, and pre-conditioning. containerised solids ($CaCO_3$) can use existing port equipment but shift the challenge to solids logistics. Early adoption will concentrate in segments whose layouts and energy profiles most readily accommodate onboard carbon capture. LNG carriers and large tankers are generally the strongest candidates due to their operational and technical profiles. Containerships can work with modular/ISO solutions, but there is an important trade-off of TEU space for equipment. Bulk carriers face the hardest retrofits due to tighter spatial constraints and more limited heat recovery potential unless on short-sea trades or regional trades where endurance demands are lower and offloading is more frequent tend to be more feasible. Liner services are better candidates than tramp because predictable port calls simplify CO_2 offloading and the relevant verification agreements required to make OCCS viable across the full Captured Carbon Product (CCP) value chain.

Successful OCCS depends on assured downstream pathways. The report documents end-to-end demonstrations from ship capture to STS/terminal transfer and industrial utilisation. and highlights the maturing North Sea sequestration backbone receiving CO_2 by ship. Yet port reception is nascent, purity specs are strict, and custody-transfer losses (flash/boil-off/venting) can erode net abatement if not engineered carefully. Building green corridors with committed reception and storage is the fastest route to bankable projects.

At IMO level, EEXI/EEDI/CII presently lack defined OCCS crediting. Lifecycle (WtW) and monitoring workstreams are progressing but not finalised. In the EU, ETS can recognise permanently stored CO_2 and thus provides the only near-term compliance value, while FuelEU Maritime awaits methodological updates before it can credit OCCS. Waste-handling and cross-border law (LC/LP, Basel) are workable along defined corridors but not yet uniform. In the interim, classification societies provide the most concrete ruleset bridging the gap to statutory codification. Eventually, the report concludes that OCCS will scale where accounting and infrastructure line up. For the time being it remains pilot-led and route specific with the potential to scale up towards 2028-2030.

For shipowners, the report recommends technology-route matching by segment and trade, early OCCS-ready design on newbuilds (space, power, stability margins), and pairing installations with firm offtake/receiving agreements on defined corridors. For ports and storage operators, priorities are reception capacity, purity alignment, and efficient custody-transfer. For regulators, the quickest unlock is clear OCCS accounting in IMO/EU measures and harmonised monitoring, reporting and verification methodologies, availability of carbon byproducts disposal pathways and clear chain-of-custody pathways. With these enablers in place, OCCS can bridge the compliance gap of the 2020s and complement the long-term fuel transition in the 2030s.

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Onboard Carbon Capture and Storage Review

1. Introduction

International Chamber of Shipping (ICS), representing over 80% of the world's fleet through its 40 national shipowner associations, is the umbrella trade association for shipowners worldwide. Within recent ICS Marine Committee discussions, the need for an independent, evidence-based OCCS study was identified by member associations as a priority area to support future decision-making. The overall objective is to deliver a thorough, up-to-date, and impartial analysis of the feasibility, costs, benefits, and challenges of deploying OCCS technologies across different vessel types and operating profiles.

The decarbonisation of international shipping is entering a decisive period, driven by increasingly stringent climate-policy frameworks, accelerating regulatory developments, and rising expectations from charterers, financiers, and cargo owners. While low- and zero-carbon fuels are expected to play a central role in achieving the sector's long-term climate objectives, their large-scale availability, cost, and infrastructure readiness remain uncertain in the near to medium term. Against this backdrop, Onboard Carbon Capture and Storage (OCCS) is emerging as a technically credible and potentially impactful transitional solution, capable of mitigating CO_2 emissions from vessels that will continue operating on conventional or transitional fuels throughout the 2030s.

This report presents a comprehensive appraisal of the current state of OCCS across all major technology families of pre-combustion and post-combustion, like membrane-based, cryogenic, and mineralisation-based pathways. It evaluates their Technology and Commercial Readiness Levels (TRLs/CRLs), integration complexity, space and stability impacts, energy demand, storage requirements, and compatibility with the operational profiles of different vessel segments. It also synthesises findings from existing and emerging pilot projects and demonstrators, providing real-world insight into performance, reliability, and value-chain interactions.

The study further examines the downstream dimension of OCCS, including port-side carbon offloading options, emerging cross-border carbon transport systems, evolving industrial utilisation markets, and the readiness of geological sequestration networks.

As regulatory clarity is one of the most critical enablers for OCCS adoption, the report includes an in-depth review of the current and developing frameworks under the IMO, EU, and key national jurisdictions highlighting areas of alignment, gaps, and the implications for compliance under future market-based measures and lifecycle-based fuel standards.

Overall, this report aims to provide shipowners, policymakers, and industry stakeholders with a neutral, technically robust, and strategically oriented foundation for decision-making. It highlights where OCCS offers realistic abatement potential in the near term, where its applicability is constrained, and what enabling conditions (i.e technological, regulatory, and infrastructural) must evolve for OCCS to play a meaningful role in supporting the maritime sector's transition toward net-zero emissions.

2. Carbon Capture and Storage (CCS) Technologies

This Section provides a comprehensive technical assessment of the full spectrum of Carbon Capture and Storage (CCS) technologies that are currently relevant or emerging for maritime applications. The objective of this section is to establish a clear understanding of how different capture pathways function, their maturity levels, and the practical considerations influencing their integration onboard ships. The analysis spans both pre-combustion and post-combustion approaches, supported by a detailed review of onboard $carbon_2$ storage options and an overview of technology vendors active in the maritime CCS space.

The section begins by examining pre-combustion technologies, including fuel reforming and thermocatalytic decomposition, which aim to remove carbon before combustion through the production of hydrogen-rich fuels or solid carbon. Their underlying principles, process steps, energy requirements and Technology and Commercial Readiness Levels are analysed, highlighting their future potential and current limitations for shipboard use.

It then proceeds to an extensive discussion of post-combustion technologies, which represent the most mature and widely demonstrated pathway for maritime deployment. These include chemical absorption, membrane separation, adsorption-based systems, cryogenic separation, and calcium looping. For each method, the report describes process configurations, capture mechanisms, performance characteristics, sensitivity to flue-gas conditions, energy demand, and operational considerations.

Following the capture technologies, the section explores onboard CO_2 storage solutions, recognising that storage capacity, stability, footprint, and system integration play a decisive role in determining overall OCCS feasibility. The discussion covers compressed gas storage, liquefied CO_2 (LCO_2), solid-carbon storage pathways, mineralised CO_2 products such as $CaCO_3$, and modular containerised configurations.

The section then provides a Vendors Overview, presenting a technology-neutral review of key industrial actors developing OCCS systems. This includes both well-established and emerging providers across various types of technologies. Their readiness levels, design approaches, pilot experience and integration requirements are summarised to give a clear picture of the current state of the market.

Finally, Section 2 concludes with an assessment of vessel-segment applicability, highlighting how layout constraints, waste-heat availability, operational patterns, and cargo-handling requirements influence the feasibility of different CCS technologies across tankers, bulk carriers, containerships, and LNG carriers. This is combined with an inventory of recent and ongoing OCCS pilot projects and demonstration trials in the maritime sector, using a structured research methodology.

Together, these components provide a robust foundation for understanding how CCS technologies operate, how they compare, and what practical considerations shape their deployment in real maritime environments, setting the technical baseline for the subsequent chapters on disposal pathways, regulatory frameworks, and strategic recommendations.

2.1 Pre-Combustion

Pre-combustion carbon-capture technologies remove carbon from the fuel stream before it enters the engine, producing a hydrogen-rich fuel that generates significantly lower CO_2 emissions during combustion. In the maritime context, pre-combustion pathways, primarily fuel reforming and thermocatalytic decomposition (TCD), offer promising long-term potential, particularly for LNG-fuelled vessels where the availability of high-purity methane provides a compatible feedstock.

2.1.1 Fuel reforming

In this pre-combustion carbon capture method, carbon is removed from the fuel stream prior to combustion (Madejski, 2022). The process typically involves converting the primary fuel, most commonly LNG, into a synthesis gas through high-temperature steam reforming. This reaction produces a gas mixture mainly consisting of hydrogen (H_2) and carbon monoxide (CO) as seen in Figure 1.

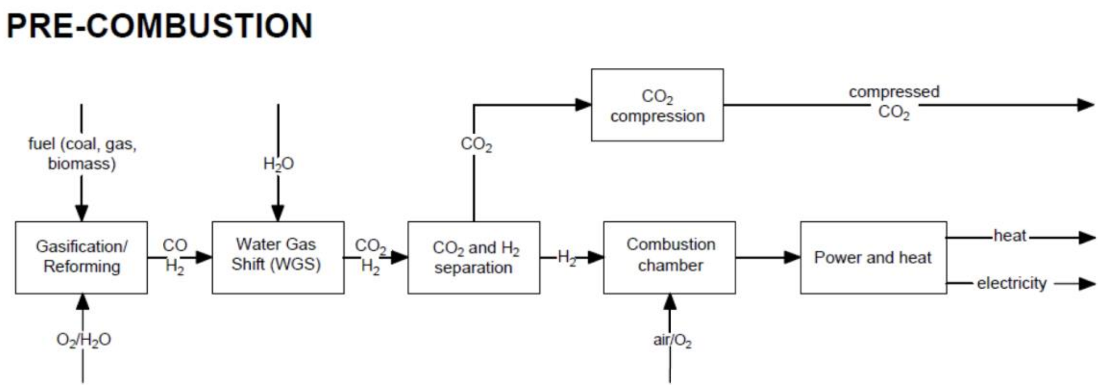


Figure 1. Block Diagram of electricity generation heat production with the use of the precombustion CO_2 capture method (National Energy Technology Laboratory, 2023)

Subsequently, the syngas undergoes a water–gas shift reaction, in which CO reacts with steam to form additional H_2 and carbon dioxide (CO_2). The resulting H_2–CO_2 mixture is then separated using gas separation technologies similar to those applied in post-combustion capture systems. The CO_2 is captured for storage or further handling, while the hydrogen can be utilised as a low-carbon energy carrier for onboard power generation.

This approach is particularly well-suited to LNG-fuelled vessels, as Steam Methane Reforming (SMR) is a mature and widely deployed industrial process that converts methane (CH_4), the primary constituent of LNG, into hydrogen (H_2) and carbon dioxide (CO_2).

A key advantage of pre-combustion capture is the significantly higher CO_2 concentration in the synthesis gas, typically around 40% by volume, compared to approximately 5–15% by volume in post-combustion exhaust gases. This higher concentration reduces the energy intensity and complexity of the CO_2 separation process. Additionally, the subsequent use of hydrogen as a fuel results in substantially lower combustion-related emissions, further enhancing the overall GHG reduction potential.

Collectively, the higher CO_2 partial pressure, the lower specific energy demand for separation, and the inherently cleaner combustion of hydrogen constitute the principal advantages of this method compared with post-combustion systems. Although these technologies are commercially proven in land-based industrial settings, they have not yet been adopted in the maritime sector due to several integration barriers. Pre-combustion systems require substantial onboard process equipment for fuel reforming, gas cleaning, and hydrogen conditioning, adding significant space, weight, and thermal-management requirements that are difficult to accommodate within existing ship layouts. Their TRL level for maritime applications is now estimated to be between 4 and 5.

2.1.2 Thermocatalytic Decomposition

Thermocatalytic decomposition (TCD) is a methane-to-hydrogen process in which methane from LNG or natural gas is cracked over a solid catalyst to yield hydrogen and solid carbon, without producing CO_2 at the reaction step. The feed gas is first desulfurised to preserve catalyst activity and then pre-heated before entering a high-temperature catalytic reactor operating typically between 600–1,000 °C. Within the reactor, methane dissociates on the catalyst surface, generating a high-purity hydrogen stream and solid carbon that deposits on the catalyst or reactor internals. Continuous or periodic removal of carbon is required to maintain reactor performance and restore catalyst activity. A process-flow diagram of the procedure is shown in Figure 2.

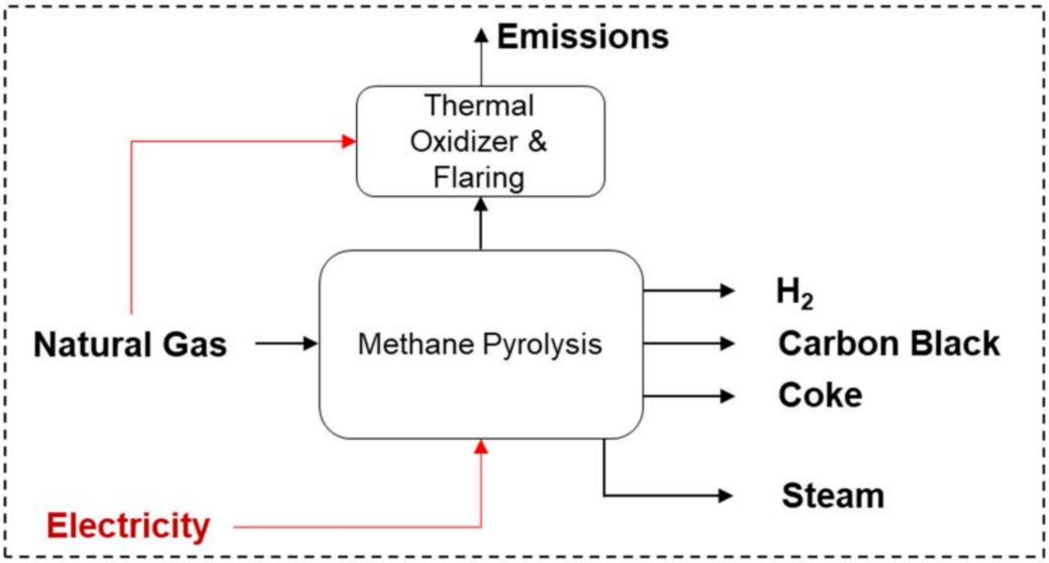


Figure 2. Schematic diagram for methane pyrolysis process (Argonne National Laboratory, 2023)

The resulting hydrogen can be used in fuel cells, internal combustion engines, or auxiliary burners, while the solid carbon, depending on its morphology (e.g., carbon black, graphitic particles), may be stored onboard, offloaded, or supplied to industrial markets. Demand for advanced carbon materials such as carbon black, graphite and graphene is expected to grow significantly toward 2030, increasing the potential value of TCD-derived by-products. (Argonne National Laboratory, 2023)

For maritime integration, key engineering considerations include heat-supply coupling (e.g., waste-heat recovery), reactor fouling management, methane-slip prevention, and the storage and handling of solid carbon over the voyage duration. Although TCD avoids the need for onboard post-combustion capture, overall climate performance depends on upstream methane management and on the disposition of the produced carbon. In the maritime sector, TCD is currently assessed at TRL 5–6, reflecting successful pilot-scale demonstrations but the absence of full-scale marine integration, as noted in the EMSA technology assessments.

2.1.3 Comparative table

In the comparative table below, a summary of the above-mentioned pre-combustion carbon capture and storage technologies is given to showcase the key advantages and disadvantages of each technology.

Table 1. Key features of Pre-Combustion methods

Criteria	***Pre-Combustion Methods***	
	Fuel Reforming	TCD – Thermo-Catalytic Decomposition
1. Maturity (TRL)	Low (TRL 4-5)	Medium Low (TRL 5-6)
2. SO_X, NO_X Removal Required	No	Yes
3. Pre-Drying Required	No	Yes (part of pre-cooling)
4. Sensitivity to Impurities (performance-wise)	Yes (reformer catalysts sensitive to S, Cl, metals)	Yes (catalyst poisoning S/metal)
5. Capture Rate (maximum range)	60%-85%	Up to 99%
6. Post-Drying Required	No	No
7. Purification Required (CO_2 stream purity %)	Yes (98-99% depending on the process)	No CO_2 stream (solid C)
8. Thermal Energy Required	High	High
9. Electric Power Required (kW)	Medium	Medium
Advantages	Produces H_2 onboard; high capture; avoids LCO_2 tanks;	Produces H_2 onboard;No CO_2 storage; solid carbon by-product
Disadvantages	High complexity; high-temp reactors; large footprint; H_2 safety; very low TRL	High-temperature reactors; catalyst poisoning, medium TRL

2.2 Post-Combustion

Post-combustion carbon capture involves technologies that extract CO_2 after fuel has been burned, treating the exhaust gas before it is released to the atmosphere. This pathway represents the most mature and extensively demonstrated approach for shipboard carbon capture. Its principal advantage for maritime deployment is that the capture system operates independently of the vessel's propulsion plant, allowing retrofit installation without altering fuel type, engine configuration, or upstream combustion processes. Section 2.2 provides an in-depth review of the five major post-combustion approaches, detailing their operating mechanisms, capture performance, energy requirements, system complexity, and integration considerations. The post-combustion technologies described below are chemical absorption, membrane separation, adsorption, cryogenic separation, and calcium looping.

2.2.1 Chemical Absorption

Chemical absorption using amine-based solvents is the most technologically mature and commercially established post-combustion carbon capture method. In land-based CCS applications, the technology has reached a Technology Readiness Level of 9, while for shipboard OCCS it is best characterised at TRL 7 to 8, reflecting the presence of pilot systems and early commercial demonstrations (Integrated Environmental Control Model Team, 2019). In this method, a liquid amine solvent selectively absorbs CO_2 from the exhaust stream, after which the CO_2 is released through thermal regeneration in a stripper column, enabling the solvent to be recirculated in a closed loop (Figure 3).

The method requires the removal of sulphur oxides and nitrogen oxides upstream, because these impurities degrade amine solvents and reduce system performance. Pre-drying is also necessary, since water must be reduced as part of the cooling step to avoid operational instability. Maximum capture efficiencies typically range from about 85 to 95 percent depending on process configuration, and post-drying is required to ensure that the outlet stream meets downstream conditioning requirements. Solvent-based systems do not normally require an additional purification step because the carbon dioxide reaches a purity of about 95 percent following regeneration.

Monoethanolamine, also known as MEA, is the most widely used solvent due to its high reactivity and well-established operational characteristics. Other solvents such as methyldiethanolamine or diethanolamine are also used in specific applications to reduce regeneration energy demand or improve stability. The underlying mechanism relies on a reversible acid–base reaction between carbon dioxide in the flue gas and the aqueous alkaline amine solution.

Chemical absorption requires a substantial thermal-energy input for solvent regeneration, while its electric-power requirement remains comparatively low. These systems are compatible with maritime retrofits because they operate downstream of the combustion unit without requiring modifications to the engine or fuel pathway. However, the space and weight demands associated with the absorber, regenerator, heat-exchange equipment and solvent-storage tanks can be considerable. Concepts that involve storing carbon dioxide temporarily in solvent rather than liquefying it require significant tank volume, which restricts layout flexibility and usable cargo capacity on many vessel types.

Operational use of chemicals introduces important safety and environmental considerations. Solvents are corrosive, and degradation byproducts such as nitrosamines and nitramines must be managed to avoid environmental harm. Periodic solvent replacement increases the need for chemical handling, transport and end-of-life treatment. Wastewater streams containing degraded solvent residues also need appropriate treatment before discharge, and freshwater makeup is needed to offset solvent losses in the absorber. These factors collectively define the principal disadvantages observed in shipboard use, in contrast to the method's advantages of high technological maturity, high capture rates and relatively low electric-power demand.

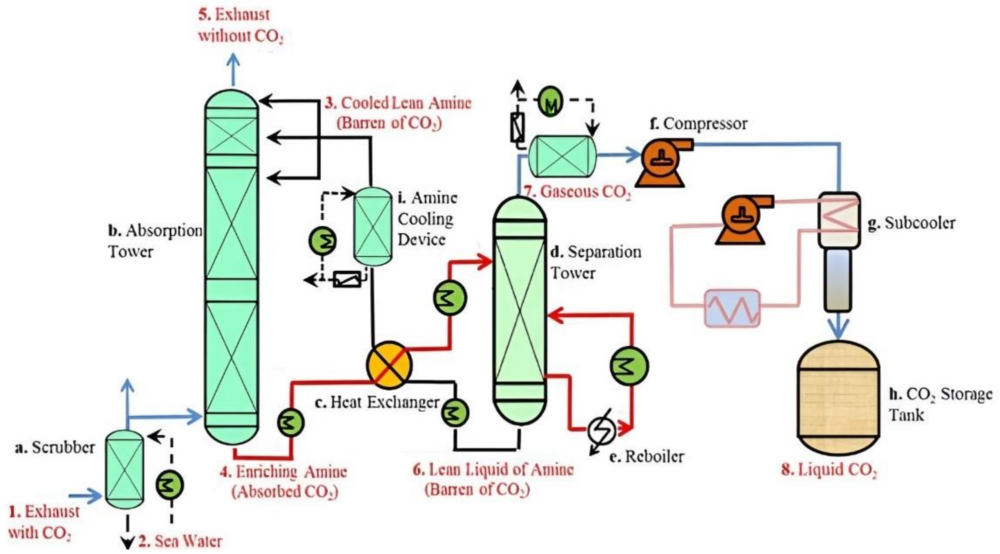


Figure 3. Process Flow diagram of chemical absorption for CO_2 carbon capture (Source: Mitsubishi Heavy Industries)

As an alternative, chemical absorption using Rotating Packed Beds (RPBs) significantly enhances mass transfer by introducing centrifugal acceleration that is one to two orders of magnitude higher than gravitational forces. This high-gravity environment dramatically increases interfacial area and reduces diffusion path lengths, enabling equivalent or superior separation performance within a much smaller reactor volume. As a result, RPB-based absorbers and strippers can achieve volume reductions of approximately 10–15 times compared to conventional packed columns operating at similar capture efficiencies. This inherent compactness, combined with reduced solvent inventory and faster dynamic response, makes the RPB methodology particularly well suited for shipboard carbon capture systems, where space, weight, and operational flexibility are critical constraints. However, RPBs have limited pilot-scale demonstration in the maritime industry at the moment.

2.2.2 Membrane Separation

Membrane separation is an advanced gas separation technology that exploits the selective permeability of membrane materials to separate carbon dioxide (CO_2) from exhaust gas streams. In a membrane-based capture system, exhaust gases are passed through membrane modules engineered to preferentially permeate CO_2, thereby separating it from the remaining flue gas components as represented in Figure 4. The CO_2-depleted exhaust is subsequently discharged, while the CO_2-enriched permeate stream is routed to downstream processing units for compression, liquefaction, or temporary storage.

In the maturity assessment, membrane systems fall within Technology Readiness Level 6 to 7 for maritime applications, reflecting laboratory validation and early pilot demonstrations rather than sustained shipboard operation. Unlike chemical absorption, membrane systems do not require upstream removal of sulphur oxides or nitrogen oxides, although their performance is sensitive to the presence of these impurities, which can accelerate membrane degradation and reduce permeability. Pre-drying is not required for operation, and no dedicated post-drying stage is necessary for carbon dioxide conditioning. Capture effectiveness typically ranges from 60 to 85 percent, a function of membrane transport limitations and the achievable pressure differential. Purification is not required beyond the inherent selectivity of the membrane because the achieved purity is directly linked to the capture rate.

Thermal-energy demand for membrane systems is low because no solvent regeneration is involved. Electric-power demand is moderate because a pressure gradient must be maintained across the membrane module, most commonly through vacuum production on the permeate side. This requirement can become a significant contributor to shipboard parasitic loads depending on operating pressure and module configuration.

Membrane systems offer several advantages for maritime integration. These include their compact and modular architecture, reduced equipment count, and the absence of chemical handling, solvent management and regeneration steps. However, these advantages are counterbalanced by notable constraints. Medium technology maturity, lower capture rates, sensitivity to exhaust-gas impurities, and the need for consistent pressure differentials limit performance in variable marine operating conditions. Membrane fouling and gradual performance decay are also concerns when the system is exposed to real exhaust-gas compositions. These disadvantages combine to constrain large-scale deployment on ocean-going vessels despite the clear integration benefits offered by the technology.

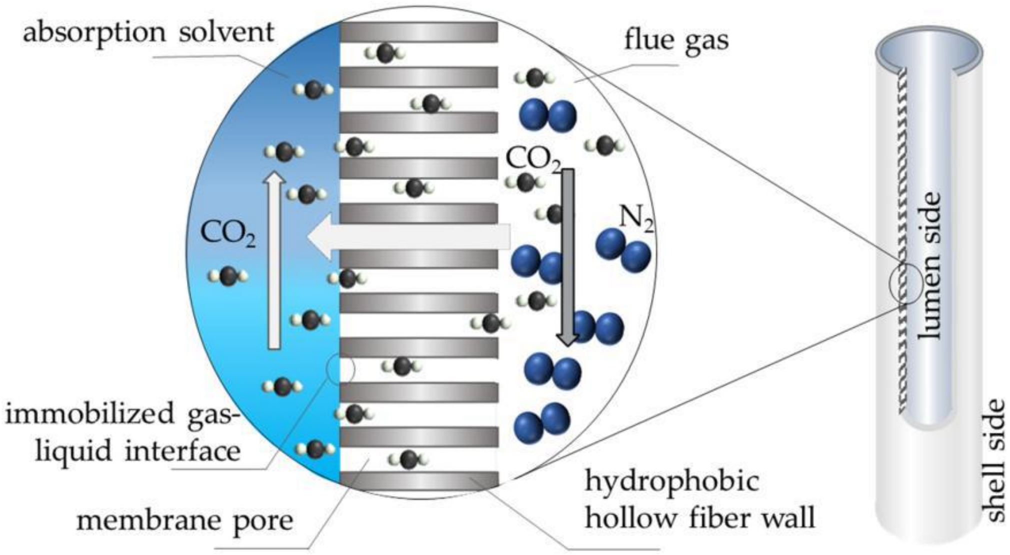


Figure 4. Schematic representation of a membrane contractor for CO_2 capture (Bozonc, 2022)

2.2.3 Physical Separation (Adsorption)

Adsorption is a post-combustion carbon capture method that uses solid sorbent materials with high specific surface areas to retain carbon dioxide molecules from flue gas streams. Sorbents such as activated carbon, zeolites and metal organic frameworks rely on physisorption or weak chemisorption to capture carbon dioxide as the gas passes through a packed or fixed bed, as illustrated in Figure 5. The fundamental distinction from absorption lies in the capture mechanism. Absorption dissolves carbon dioxide into a liquid solvent and later releases it through thermal regeneration, whereas adsorption binds carbon dioxide directly onto the surface of a solid material.

In typical adsorption systems, flue gas enters a sorbent bed where carbon dioxide is selectively retained. Once saturated, the sorbent must be regenerated through temperature swing adsorption, pressure swing adsorption or combined modes, restoring the material for cyclic operation. Adsorption technologies require pre-drying of the gas stream, because materials such as zeolites and metal organic frameworks preferentially adsorb water vapour, which reduces carbon dioxide uptake. Adsorption systems are also sensitive to sulphur oxides and nitrogen oxides, which can irreversibly degrade sorbent performance; therefore, upstream gas cleaning is required to ensure acceptable operational longevity.

Capture rates reported for adsorption fall within the range of about 80 to 90 percent under controlled conditions, although real performance varies significantly with impurity levels and moisture content. Adsorption does not normally require a dedicated purification stage because the carbon dioxide purity is determined by the regeneration process rather than by solvent chemistry. Thermal energy requirements for regeneration are medium relative to liquid solvent systems, and electric-power demand is low, since no solvent circulation or significant pumping loads are involved.

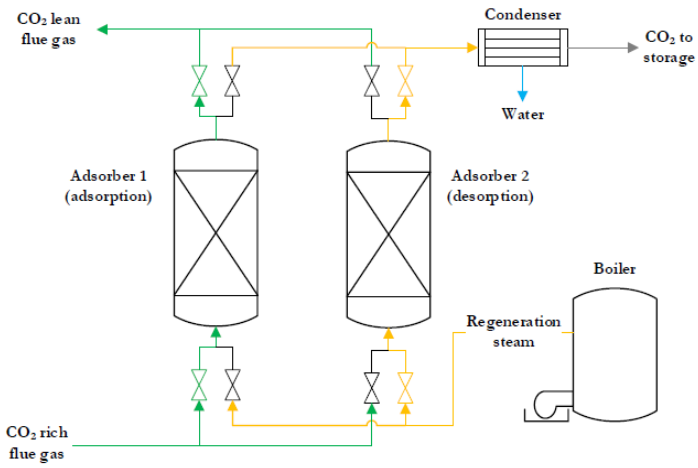


Figure 5. Schematic of a fixed bed adsorber system (Pereira, 2021)

Despite advantages such as the absence of liquid chemicals, reduced corrosion risk and the possibility of lower regeneration energy compared with solvent-based systems, adsorption systems present several disadvantages for maritime deployment. Pre-drying requirements increase system complexity, sorbent materials can degrade rapidly in the presence of impurities and water vapour, and the cyclic nature of regeneration imposes operational constraints. Space requirements are also nontrivial because multiple beds are needed to maintain continuous operation.

Due to these limitations and the very limited pilot-scale testing conducted within the maritime sector, adsorption-based carbon capture currently stands at Technology Readiness Level 3 to 4 in shipboard applications. Given this low maturity level and the absence of commercial demonstrations, the method is not further developed in the Vendors Overview.

2.2.4 Cryogenic Separation

Cryogenic separation is a post combustion carbon capture method that exploits differences in boiling points among exhaust gas constituents to isolate carbon dioxide through sequential cooling, compression and condensation under low temperature and elevated pressure conditions, as shown in Figure 6. Before cryogenic processing, water vapour must be removed to avoid freezing in the refrigeration system. Cryogenic separation is also sensitive to impurities, as the presence of water and acid gases can lead to ice formation or solid deposits that compromise heat exchanger performance.

The method typically achieves carbon dioxide purities close to 99 percent once phase change occurs, and it does not rely on chemical solvents or reagents. This absence of chemical inventory eliminates concerns related to solvent degradation, nitrosamine formation, corrosive by products or the requirement for solvent purification. Cryogenic systems also do not require post drying or downstream purification stages because the phase change itself produces a high purity carbon dioxide stream.

Capture rates for cryogenic systems are usually in the range of about 90 to 99 percent when inlet concentrations are sufficiently high. However, the method is intrinsically constrained by its energy demand. Deep refrigeration and repeated compression impose a high thermal and electrical load, making cryogenic separation energy intensive relative to other post combustion capture technologies. Electric power demand is particularly high due to the operation of refrigeration units and compressors.

The method does not require sulphur oxide or nitrogen oxide removal as part of the capture mechanism, yet its performance is indirectly influenced by these impurities because they contribute to freezing risks or operational instability. For this reason, some degree of upstream cleaning is typically necessary before the gas stream can enter cryogenic equipment.

Cryogenic carbon capture offers several advantages, including very high carbon dioxide purity, the absence of chemical handling, low thermal energy demand relative to solvent regeneration, and no requirement for gas purification stages. Its disadvantages include high electrical power demand, high sensitivity to the presence of water vapour, and limited applicability at low inlet carbon dioxide concentrations. Economic viability generally requires carbon dioxide fractions above about 50 percent, which is significantly higher than those found in marine engine exhaust.

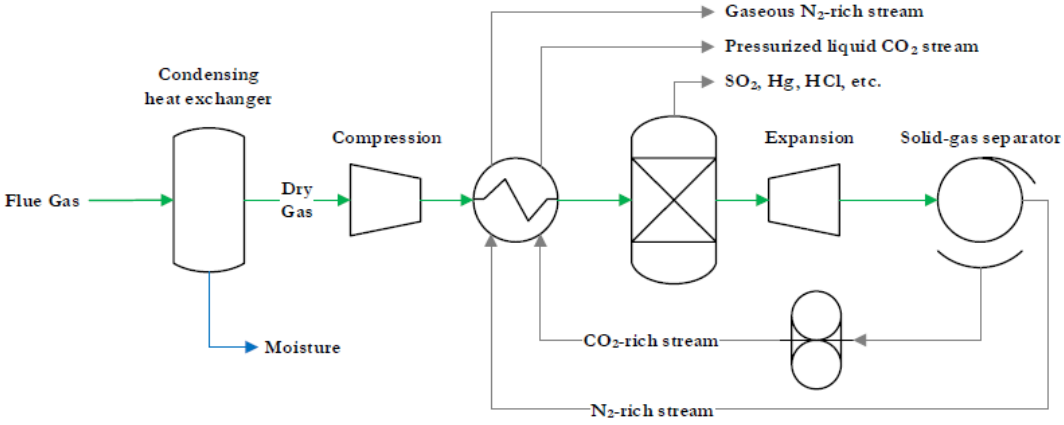


Figure 6. Cryogenic carbon capturing process block diagram (Pereira, 2021)

Overall, cryogenic carbon capture exhibits low to medium technological maturity for shipping applications, with its Technology Readiness Level (TRL) currently estimated at TRL 4–5, reflecting limited pilot-scale demonstrations and a lack of operational experience in real-world marine environments.

2.2.5 Calcium Looping

Calcium looping is a post-combustion carbon capture technology that operates through a cyclic, two-stage process consisting of carbonation and calcination. In the carbonation stage, solid calcium oxide (CaO), commonly referred to as quicklime, is loaded onboard a vessel equipped with a carbonator reactor. Exhaust gases are directed through the reactor, where CO_2 reacts with CaO to form solid calcium carbonate ($CaCO_3$), or limestone (Figure 7). The resulting $CaCO_3$ is discharged from the reactor and stored onboard until the vessel reaches port. (Mantripragada, 2017)

The onshore calcination stage, when employed, involves heating the collected calcium carbonate to release a concentrated carbon dioxide stream and regenerate calcium oxide. The regenerated sorbent can then be returned to vessels equipped with calcium looping systems, while the carbon dioxide is directed either to geological storage or to utilisation pathways such as the production of synthetic fuels or construction materials. Alternatively, the calcium carbonate produced onboard may be offloaded directly as a marketable raw material, eliminating the need for calcination.

In its performance characteristics, calcium looping is assessed at Technology Readiness Level 6 to 7 for maritime applications, following successful shipboard pilots. The process requires pre removal of sulphur oxides and nitrogen oxides because these impurities react irreversibly with calcium oxide and reduce sorbent capacity. Pre-drying of the flue gas is also required, since water vapour affects carbonation efficiency and increases the formation of unwanted hydrated by products. The method is sensitive to impurities including nitrogen oxides and sulphur oxides, which impact reaction kinetics and sorbent regeneration potential. Capture rates typically fall within a range of about 70 to 95 percent depending on reactor configuration and sorbent cycling behavior. Post drying is required when the captured product is transferred for further processing. No purification step is needed because calcium carbonate is produced directly as the capture product. Thermal-energy demand during shipboard operation is low because carbonation is exothermic and the regeneration step takes place onshore. Electric-power demand onboard is also low because only solids handling and gas transport require auxiliary energy input.

Calcium looping provides several advantages for shipboard integration. Carbon dioxide is stored in a stable solid phase that does not require compression, liquefaction or cryogenic systems. The process employs nontoxic, widely available materials and avoids chemical solvents entirely. Onboard energy requirements are low and the approach offers potential for lower operational expenditure compared to solvent based systems. Its primary disadvantages include the energy intensive nature of producing calcium oxide from natural limestone, uncertainty surrounding reliable port side supply chains for sorbent distribution, and the additional operational burden associated with managing large volumes of solid calcium carbonate. Although calcium carbonate is nonhazardous, its storage footprint onboard is substantial, and the management of the calcium carbonate water mixture may raise regulatory and environmental considerations as deployment scales.

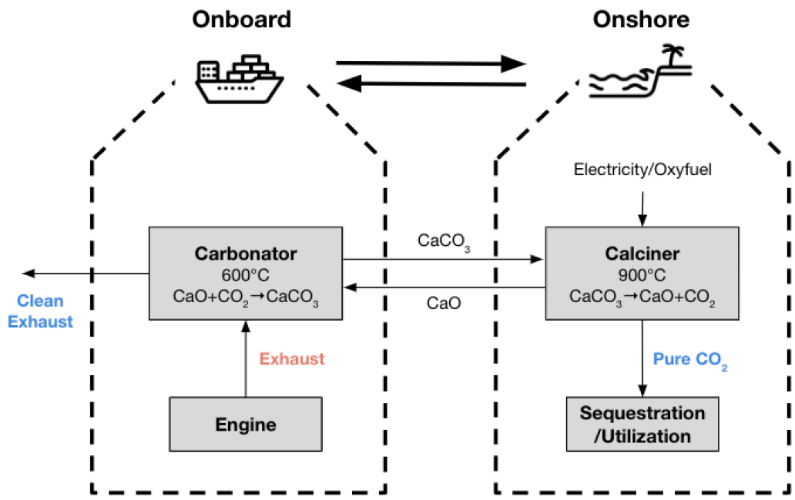


Figure 7. Calcium Looping (Mineralisation) process (Source:Seabound)

2.2.6 Comparative table

In the comparative table below, a summary of the above-mentioned post-combustion carbon capture and storage technologies is given to showcase the key advantages and disadvantages of each technology.

Table 2. Key features of Post Combustion Methods

Criteria	Post-Combustion Technologies for CO_2 capture				
	Chemical Absorption (solvents)	Membrane Separation (filtration)	Physical Separation (Adsorption)	Cryogenic Separation (cooling)	Calcium Looping (mineralisation)
1. Maturity (TRL)	High (TRL 7-8)	Medium (TRL 6-7)	Low (TRL 4-5)	Low (TRL 4-5)	Medium (TRL 6-7)
2. SO_X, NO_X Removal Required	Yes	No	No (performance sensitive)	No (part of the process)	Yes
3. Pre-Drying Required	Yes (part of pre-cooling)	No	Yes	Yes	Yes
4. Sensitivity to Impurities (performance-wise)	Yes (NO_x ,SO_x)	Yes (NO_x, SO_x)	Yes (H_2O, NO_x, SO_x)	Yes (H_2O)	Yes (H_2O, NO_X, SO_X)
5. Capture Rate (maximum range)	85%-95%	60%-85%	80%-95%	90%-99%	70%-95%
6. Post-Drying Required	Yes	Yes (part of purification stage)	No	No	No
7. Purification Required (CO_2 stream purity %)	No (95%)	Yes (85% - linked with capture rate)	No (95% - linked with capture rate)	No (99.9%)	N/A (solid carbonate)
8. Thermal Energy Required	High	Medium	Medium	Low	Medium
9. Electric Power Required (kW)	Low	Medium	Low	High	Low
Advantages	High TRL, High Purity, High Capture Rates, Low Electric Power Required	Simplicity (less equipment, less moving parts), No Pre-Drying Required	No Purification Required, Low Electric Power Required	High Purity, High Capture Rates, Low Thermal Energy Required, No Purification Required	Permanent storage, lower energy demand, no pressurised CO_2 storage onboard
Disadvantages	Solvents are toxic/corrosive, High Thermal Energy Required, Pre- and Post-Drying Required, Space Requirements	Medium TRL, Low Capture Rates, Purification Required, Medium Thermal & Electric Power Required	Pre-Drying Required. Medium Thermal Energy Required, Space Requirements	Low TRL, High Electric Power Required, Pre-Drying Required	Very bulky solids, disposal of Calcium Carbonate, Lack of large-scale operation experience

Overall, the suitability of post-combustion CCS technologies for maritime applications is primarily constrained by onboard energy demand, space limitations, and system complexity. Chemical absorption currently represents the most viable near-term solution, supported by its high TRL, high CO_2 capture efficiency, and proven operational track record, despite challenges related to high thermal energy consumption, solvent degradation, and space requirements.

Calcium looping shows medium-term potential due to its high capture rates, no requirement for onboard CO_2 storage and relatively low operational costs; however, its deployment is limited by lower maturity, material replacement needs, and unresolved issues related to by-product handling (calcium carbonate) and regulatory acceptance. Membrane separation and adsorption technologies, while attractive due to their compactness, modularity, and lower environmental risks, remain constrained by lower capture efficiencies, sensitivity to exhaust gas composition, and insufficient demonstration under marine operating conditions. Cryogenic separation is currently the least suitable option for onboard application, as its high electrical power requirements and refrigeration complexity outweigh its benefits.

2.3 Storage options for Onboard Carbon Capture

The selection of onboard CO_2 storage pathways is a central determinant of OCCS feasibility, as it directly influences vessel stability, space utilisation, energy consumption, and interface requirements with port infrastructure. While several storage modalities are theoretically possible, only a subset exhibit the necessary maturity, density characteristics, and integration potential for commercial deployment in deep-sea shipping. The following subsections provide a comparative assessment of the principal storage forms; compressed gaseous CO_2, liquefied CO_2 (Figure 8), solid carbon from pyrolytic processes, inorganic carbonates resulting from mineralisation pathways, and modular containerised solutions, focusing on their technical characteristics, engineering integration challenges, and implications for shipboard operation.

Figure 8. Liquified CO_2 storage tank (Source: Bl-Cryo)

2.3.1 CO_2 compression

Compressed CO_2 represents the most straightforward method of containment, relying on pressure vessels operating typically in the 50–70 bar range under near-ambient temperature. From a thermodynamic perspective, gaseous CO_2 at these pressures remains relatively low in density compared with cryogenic liquid storage, resulting in a substantial volumetric penalty. This renders compressed storage systems disproportionately demanding in terms of space and weight for vessels with multi-tonne capture rates or long voyage durations. (Ahmed, 2025)

Although pressure-vessel storage is widely used in industrial gas applications, its applicability to deep-sea shipping is limited by the low mass-to-volume ratio achievable and the structural reinforcement required to accommodate high-pressure tanks. Consequently, compressed CO_2 is generally regarded as a niche option, potentially viable for small vessels, ferries, or short-sea operations where capture volumes are modest and the simplicity of non-cryogenic systems is desirable.

2.3.2 CO_2 liquefaction

Liquefied CO_2 storage constitutes the dominant and most mature pathway for maritime OCCS. When cooled to cryogenic temperatures (approximately –55°C to –35°C) and maintained at relatively low pressures (6–20 bar, depending on tank design), CO_2 achieves a density typically exceeding 1,050–1,100 kg/m^3, enabling compact storage relative to compressed gas or mineralised solids. This high volumetric efficiency, combined with the existence of well-established industrial LCO_2 supply chains, renders cryogenic storage the prevailing choice in demonstrated marine pilots.

Cryogenic containment requires C-type pressure vessels, associated refrigeration systems, insulation, and careful integration into the vessel's structural layout. The mass of both the tanks and their contents contributes to increased lightweight tonnage and may necessitate adjustments to ballast management or deck reinforcement. Nevertheless, because LCO_2 interfaces seamlessly with emerging port infrastructure, particularly in Northern Europe and East Asia, this mode of storage offers the clearest alignment with future ship-to-shore CO_2 logistics chains.

As such, LCO_2 storage is generally considered the baseline configuration for chemical absorption and membrane-based OCCS systems, particularly on tankers, LNG carriers, and large container vessels where deck availability and stability margins are sufficient to accommodate cryogenic tanks. (Ahmed, 2025)

2.3.3 Solid Carbon

Certain pre-combustion pathways, such as methane pyrolysis or catalytic fuel reforming, avoid the need to store CO_2 directly. Instead, the carbon content of hydrocarbon fuels is converted into solid carbon, while the remaining hydrogen-rich fuel is combusted in the engine. The resulting solid carbon is chemically stable, non-volatile, and comparatively benign from a safety perspective. (U.S. Department of Energy / Argonne National Laboratory, 2023)

However, the volume of solid carbon generated per unit of fuel is substantial, and the bulk density of the material is markedly lower than that of LCO_2. This leads to significant storage requirements, which limit the applicability of pyrolytic OCCS to vessels with ample deck or hold space, or to short voyages permitting frequent offloading. Additionally, the post-voyage handling chain for solid carbon is underdeveloped, with limited standardised utilisation or disposal routes. Therefore, this option seems technologically intriguing, particularly for LNG-fuelled vessels seeking high reductions in lifecycle emissions.

2.3.4 Mineralised CO_2 (Calcium carbonate and Related Carbonates)

Mineralisation processes convert captured CO_2 into stable inorganic carbonates, most commonly calcium carbonate ($CaCO_3$), via reactions with calcium-based sorbents or alkaline slurries. The resulting product is chemically inert, non-hazardous, and compliant with long-term storage or recycling options. Marine demonstrations have shown that mineralisation can operate in modular form factors (e.g., containerised units), making it attractive for vessels where chemical containment hazards must be minimised.

Mineralisation, however, exhibits a significant volumetric penalty. Each tonne of CO_2 captured yields more than two tonnes of carbonate, imposing large storage demands relative to LCO_2. Furthermore, mineralisation requires continuous supply of sorbent materials and the management of solid by-products, both of which place additional demands on vessel logistics and deck space. (IMO, 2025)

As a result, while mineralisation remains less scalable for long-haul, low-frequency trades, it may hold distinct advantages in liner shipping, short-sea routes, and coastal trades where regular port access mitigates the storage-intensity challenge. In such contexts, mineralisation offers a safety-oriented alternative to cryogenic storage without imposing prohibitive space penalties over extended durations.

2.3.5 CO_2 containerised storage

Containerised storage solutions, whether implemented as ISO tanks for compressed or liquefied CO_2, or as modular mineralisation units, represent an emerging design philosophy prioritising modularity, operational flexibility, and ease of port handling. These solutions minimise the need for permanent structural modifications, allowing units to be swapped or removed at port in a manner analogous to conventional cargo equipment.

While attractive for retrofits, containerised systems offer limited storage capacity and higher relative mass and footprint compared with fully integrated systems. Their applicability is therefore greatest in early deployment phases, on regional or short-voyage routes, or on vessels with intermittent rather than continuous capture requirements.

2.4 Vendors Overview

Before assessing individual technology vendors, LR Advisory conducted a comprehensive screening of the current landscape of onboard carbon capture and storage (CCS) solutions available to the maritime sector. This review covered the full spectrum of pre-combustion, post-combustion, and membrane-based systems, evaluating each technology's maturity, integration complexity, operational demands, and applicability to different vessel types and fuel configurations. The objective of this screening was to establish a clear understanding of the technical readiness, commercial readiness, and operational viability of emerging CCS concepts, while identifying the key advantages, limitations and deployment considerations associated with each approach. The analysis also considered the evolving regulatory framework, class-approval pathways and port-offloading constraints in order to provide shipowners with an informed, technology-neutral view of the current CCS market.

2.4.1 Thermocatalytic Decomposition

2.4.1.1 Hycamite

Hycamite applies thermocatalytic decomposition (TCD) to split methane into hydrogen and solid carbon, enabling hydrogen production without generating CO_2 as a by-product. The technology relies on a specially developed catalyst that operates at elevated temperatures, is fully regenerable, and allows the reaction to break methane bonds efficiently. Compared with electrolysis, the process requires only around 13% of the energy input, making it significantly less energy-intensive for onboard hydrogen generation. Baseline testing has demonstrated the capability to produce approximately 100 kg of hydrogen per hour while generating about 300 kg of solid carbon and consuming around 400 kg of methane per hour. For maritime use, the system requires a reactor, heater, cooling and filtration systems, and pneumatic transfer equipment, as shown in Figure 9, to move the solid carbon to a buffer silo. Operating conditions depend on temperature, pressure, and exhaust composition, all of which influence carbon output and hydrogen purity.

In terms of readiness, Hycamite is currently at Technology Readiness Level 5, with land-based tests ongoing for a 100 kg/h hydrogen production unit. A marine-specific solution is expected to follow a similar configuration. Commercial readiness is at level 4, indicating early-stage deployment potential. The company is collaborating with Wärtsilä on maritime applications and has secured investment from CMA CGM and Mitsui OSK Lines, signaling growing confidence in the technology's scalability and relevance for shipping.

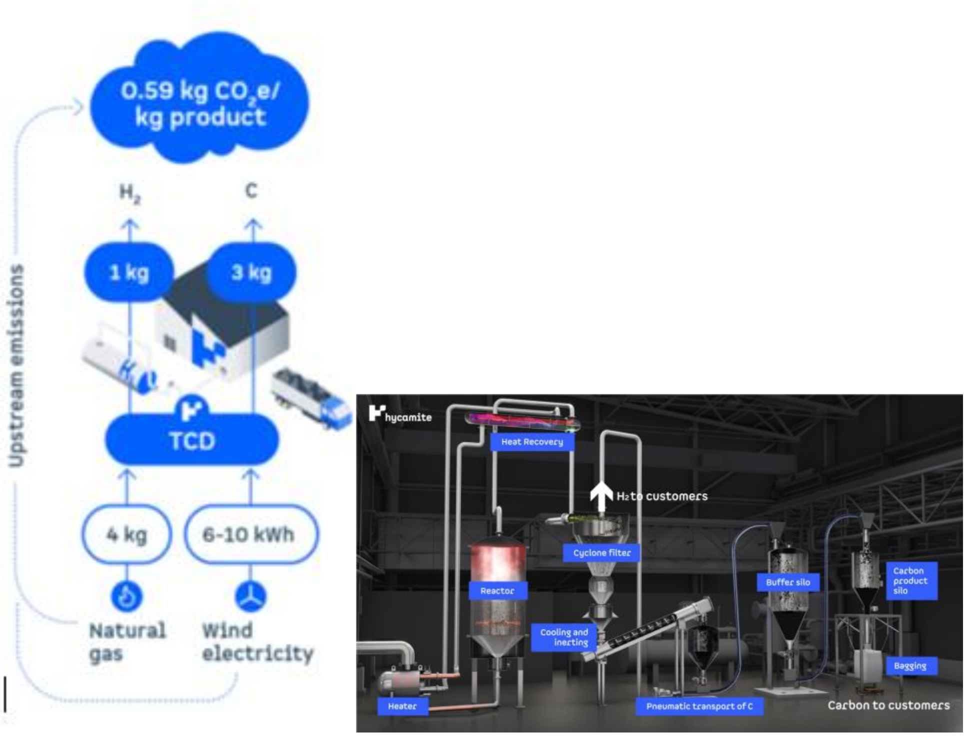


Figure 9. Hycamite system flow process (Source:Hycamite)

Operationally, the system requires electricity and catalyst materials as inputs, while producing hydrogen gas and solid carbon as outputs. This is shown in Figure 9 as well. In theory, methane decomposition can avoid up to 99% of CO_2 emissions since carbon is captured in solid form rather than requiring liquefaction or compression. The solid carbon is stored onboard and offloaded at port, whereas the hydrogen must be placed in a buffer tank and consumed shortly after production due to storage limitations. This configuration avoids the challenges associated with handling gaseous or liquid CO_2 onboard but introduces the need for safe storage of carbon powder in an inert environment.

From a regulatory perspective, the technology has achieved Approval in Principle from DNV, confirming that the concept meets fundamental safety and installation requirements. Installation complexity is expected to influence project timelines, especially for retrofits, while maintenance intervals are estimated at six to twelve months, with catalyst replacement typically occurring every five years. The system can be considered for both newbuilds and retrofits, although newbuild integration may allow more efficient placement of the reactor and storage systems.

Despite its advantages, the technology also faces certain limitations. Producing hydrogen onboard requires a relatively large processing unit, and the handling of fine carbon powder necessitates inert storage conditions to avoid safety risks. Hydrogen itself must be used rapidly, as long-term storage onboard is not practical at large volumes. The system still requires close monitoring, with some processes better supervised in person rather than relying solely on remote operation. In addition, the presence of SO_x and NO_x in the exhaust gas of some engines can reduce catalyst effectiveness, meaning upstream gas cleaning may be necessary. Lastly, capital expenditure remains significant, which may limit adoption without clear operational or regulatory incentives.

2.4.1.2 Rotoboost

Rotoboost employs a thermocatalytic decomposition (TCD) process that continuously converts natural gas into hydrogen and solid carbon using a specially formulated liquid catalyst. In this system, methane is split into hydrogen while the resulting solid carbon is either removed through filters or allowed to settle within the catalyst medium. The TCD reaction produces high-value solid carbon forms, primarily graphene and graphene nanoplatelets, whose morphology can be tuned according to feedstock composition and system operating requirements. These carbon products can serve as precursors for applications such as advanced batteries, carbon-reinforced composites, or other industrial processes. Hydrogen generated through the TCD process can be blended directly into the vessel's fuel system, providing a low-carbon hydrogen stream capable of enhancing combustion characteristics in dual-fuel engines. The system configuration and process flow are shown in Figure 10. Carbon is produced in solid form at temperatures of approximately 850–950 °C and pressures of 1–15 bar. As with similar thermocatalytic technologies, the absence of CO_2 formation during methane cracking enables a theoretical carbon capture rate approaching 99%, with carbon stored onboard in a dry, inert environment prior to offloading.

Rotoboost is currently at Technology Readiness Level 6 and Commercial Readiness Level is 5, indicating that the system has undergone prototype demonstration and is progressing toward full vessel integration. The company has obtained Approvals in Principle from ABS, Lloyd's Register, Bureau Veritas, and RINA, showing that multiple classification societies recognise the concept's safety and feasibility for maritime deployment. The first prototype system was released in 2021, followed by DNV and ABS AIPs in 2022, and additional AIPs from LR (Pre-combustion Hydrogen/TCD concepts (ROTOboost)), BV, and RINA in 2023. Although the technology is considered technically mature enough for onboard deployment, further development work is ongoing to validate reliability, operability and consistent catalyst performance under real maritime conditions.

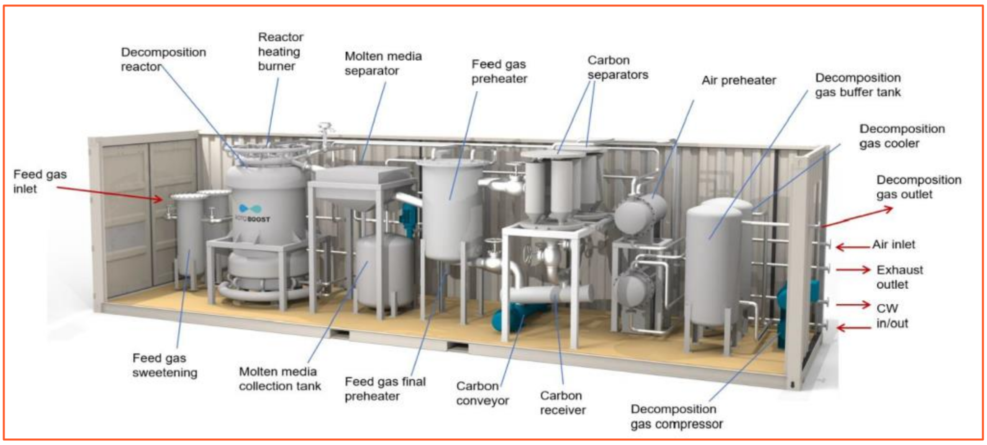


Figure 10. Rotoboost system components and process (Source: Rotoboost)

Operationally, Rotoboost requires electricity and catalyst materials as inputs, while generating hydrogen gas and solid carbon as outputs. The system's architecture must be installed within a dedicated machinery space due to its size, operational temperature and catalyst handling requirements. The solid carbon produced must be processed and stored safely prior to offloading, and in some cases Rotoboost has expressed an ambition to buy back a portion of the carbon produced to commercialise it for industrial use. Hydrogen production of around 181 kg/h is technically feasible, although this depends heavily on vessel integration, thermal management and overall system sizing.

Despite its benefits, several limitations influence deployment. The system imposes significant structural and spatial requirements on the vessel to support both the catalytic reactor and the resulting carbon storage tanks. Additional energy demand is created by the need to concentrate, process and handle the catalyst and carbon flows. CAPEX and OPEX are high relative to alternative CCS options, and economic viability is often assessed over a three- to five-year payback horizon. The system's efficiency is also sensitive to methane slip in dual-fuel engines, and while hydrogen injection can help reduce methane slip, the overall performance still depends on stable upstream engine operation and gas quality.

2.4.2 Chemical Absorption

2.4.2.1 Carbon Ridge

Carbon Ridge uses a compact post-combustion chemical absorption system designed to capture CO_2 from the ship's existing exhaust gas stream. Exhaust gas is diverted into the capture unit, where proprietary solvent formulations absorb the CO_2, after which the solvent is regenerated in a controlled process that separates the CO_2 for liquefaction and storage, as shown in Figure 11. A distinguishing feature of the Carbon Ridge system is the use of a centrifugal contactor design, which replaces the large packed towers found in conventional chemical absorption units and significantly reduces the equipment footprint, enabling installation on both newbuild and existing vessels. The system is capable of operating at lower pressures and is highly responsive to variation in flue gas temperature, relying on supplemental heaters when exhaust temperatures fall below approximately 300°C.

Carbon Ridge has reached Technology Readiness Level 7, meaning that the capture technology is considered ready for commercial deployment on operating vessels. The company is progressing through CRL 6, working toward an integrated shipboard pilot system. In 2025, the first fully integrated Carbon Ridge system is installed on a Scorpio Tankers vessel as part of a live operational test. The company has already demonstrated containerised pilot units and holds Design Basis Approval from DNV, indicating that the system meets the fundamental requirements for maritime installation and safety. Installation is designed to fall within a standard dry-dock period, making the solution attractive for retrofits.

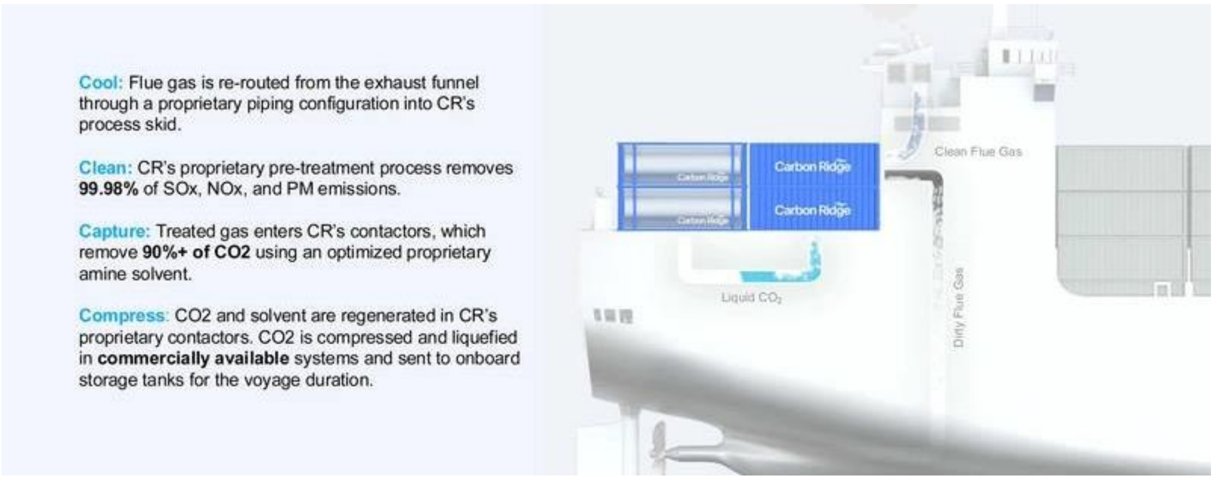


Figure 11. Carbon Ridge system properties

The system requires electricity, heat, and solvent materials as inputs, and generates a stream of liquefied CO_2 for storage in dedicated tanks. The theoretical capture efficiency exceeds 90%, although actual performance depends on engine load, exhaust gas temperature, and solvent management. Liquefaction requires significant electrical power, around 250 kW for a system capturing approximately 185 metric tonnes of CO_2 per day, and uses seawater from hull-mounted chests as the primary cooling medium.

Deployment is affected by several constraints. Structural reinforcement is needed at specific locations to support the capture unit and CO_2 storage tanks, especially on older vessels or those with limited deck space. The system requires steam for solvent regeneration; this steam can be taken from the vessel's existing systems or supplied through additional machinery, which can increase energy consumption. The refrigeration and liquefaction systems add further electrical demand, and their integration may require electrical system upgrades. Despite the technology's functional maturity, CAPEX remains high relative to simpler aftertreatment systems, although this is partially offset by the absence of catalyst consumption and the modular nature of the capture unit.

2.4.2.2 Value Maritime

Value Maritime integrates post-combustion CO_2 capture into its proprietary Filtree System, a hybrid exhaust-gas cleaning platform that combines SO_x scrubbing, particulate reduction, and carbon-capture functionality. CO_2 is removed from the exhaust using a closed-loop amine absorption and regeneration cycle, in which the solvent is cyclically washed, regenerated and re-loaded (amine exchange) to maintain capture performance. The regenerated solvent absorbs CO_2 in the absorber column, while spent solvent is thermally treated in the regenerator using heat from vessel auxiliaries or dedicated boilers.

As seen on Figure 12, captured CO_2 is transferred into the “CO_2 Battery”, a modular tank or container designed to store CO_2-rich solvent or liquefied CO_2 until offloading. This modular approach avoids the need for onboard liquefaction and enables rapid exchange of full and empty CO_2 Batteries during port calls. The system typically operates between 6–20 °C, maintaining stable capture rates under variable engine load. Under standard marine operating profiles, Value Maritime reports capture efficiencies of approximately 90%.

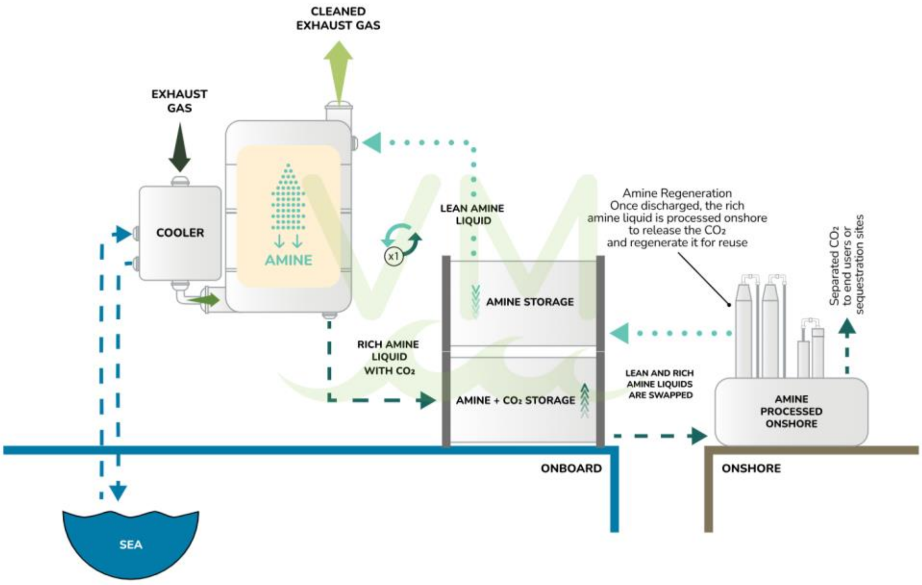


Figure 12. Operating principle of the Value Maritime Filtree System

With installations on Ardmore Shipping, X-Press Feeders, and Eastern Pacific Shipping vessels, the technology has reached TRL 8 and CRL 8, having demonstrated full shipboard capture, offloading operations, and certification for commercial use. The CO_2 Battery currently stores approximately 200 t CO_2, corresponding to around nine days of sailing at ~40% capture; additional storage may be required for longer voyages.

Operational constraints include the need for sufficient steam or heat input for solvent regeneration, additional redundancy on vessels without surplus thermal capacity, and the space and weight requirements associated with the CO_2 Battery and solvent-management systems. Wider deployment will depend on the availability of ports equipped to receive CO_2 and on evolving regulations governing CO_2 handling, transport, and custody transfer. Although less energy-intensive than full onboard liquefaction, the system still contributes to incremental fuel consumption and must be evaluated within vessel-specific energy and space constraints.

LR has signed an Approval In Principle to Amine absorption system from Value Maritime and a project-specific approval (Filtree capture and LCO_2 storage) after evaluating the technologies by applying EACCS/RBC.

A notable milestone in OCC adoption is Eastern Pacific Shipping's Pacific Cobalt retrofit with Value Maritime's Filtree OCCS, which became the first ship to receive an OCCS class notation from LR. The EACCS (Amine, HFO) notation confirms that materials, structures, containment, piping, refrigeration, electrical/control, safety systems and vessel integration were verified, and that the captured CO_2 is stored onboard for subsequent transfer to shore for processing. This public case provides a citable reference for ship-to-shore interface and confirms LR's oversight scope during installation and operation. The vessel and OCC system can be seen in Figure 13.

Figure 13. The PACIFIC COBALT (9788617) and OCC system from Value Maritime Filtree

2.4.2.3 Ionada

Ionada, as depicted in Figure 14, combines conventional amine-based chemical absorption with porous ceramic membrane technology to capture CO_2 from the ship's exhaust stream. Exhaust gas is routed through the membrane contactor, where ceramic hollow-fibre tubes allow the solvent to absorb CO_2 efficiently while preventing direct mixing of the liquid solvent with the gas stream. This membrane design increases surface area, improves solvent utilisation, and reduces the overall system footprint compared with traditional absorption towers. The CO_2-rich solvent is subsequently stripped at elevated temperatures, regenerating the amine and producing a stream of CO_2 suitable for liquefaction and cryogenic storage at approximately 15–18 bar. The system generally operates at exhaust flow rates equivalent to those produced by a 300 kW combined engine output.

Ionada is at Technology Readiness Level 7, with multiple maritime trials scheduled, including installations on containerships, bulk carriers, and Ro-Ro vessels. Exxon has already deployed the company's 4×40 ft containerised unit for a 25-day feasibility campaign on an FPSO. From a commercial perspective, the company is at CRL 5, having secured funding support from several shipping customers and moving toward an industrial-scale demonstrator targeted for installation in early 2026. Classification approvals include BV Approval in Principle, and installation is typically completed during a five-week dry-dock period. Annual maintenance is required, with a minimum service life of ten years for key system components.

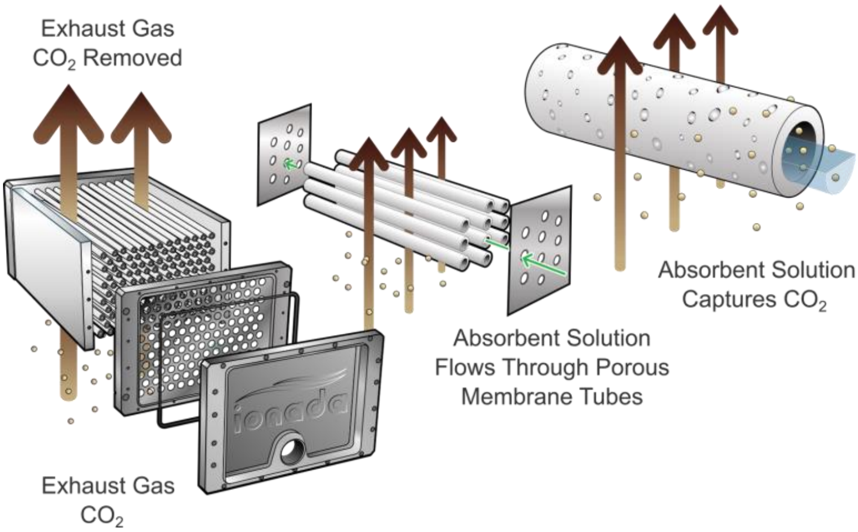


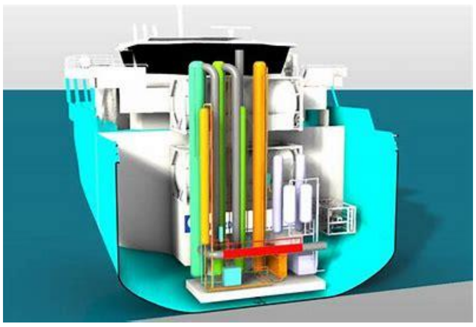
Figure 14. Ionada Technology process

Operationally, the system requires electricity, heat, solvent and membrane modules, while producing a liquefied CO_2 stream that is stored using cryogenic equipment. The theoretical capture efficiency can reach up to 95%, depending on solvent formulation, membrane performance, and exhaust gas conditions. CO_2 is stored in liquefied form, and the system is compatible with integration into existing LNG-fuelled vessel designs, although additional energy is required to maintain liquefaction temperatures. Amine consumption is moderate, though some degradation occurs at higher temperatures, requiring periodic replacement of approximately 1.5% annually.

Despite its advantages, Ionada faces several challenges. Amine solutions corrode mild steel, necessitating robust material selection for piping and vessels. The presence of ammonia in LNG exhaust streams requires the installation of a polishing catalyst to ensure safe operation, while membrane integrity must be carefully monitored to avoid solvent leakage. LNG-fuelled carriers also require additional energy to cool CO_2 to storage temperatures below –67°C, increasing parasitic load. While capture rates are high, the technology's long-term commercial performance will depend on reliability of the membrane modules and the availability of port infrastructure to offload liquefied CO_2.

2.4.2.4 Carbotreat

Carbotreat's system captures CO_2 from exhaust gas using an amine-based absorption process housed within a compact absorber–stripper configuration. Exhaust gas enters the absorber where solvent captures the CO_2, and the CO_2-rich solvent is subsequently heated in the desorber at around 130°C to release purified CO_2 as illustrated in Figure 15. The clean gas exits the system at near-ambient pressure, and the captured CO_2 is dried, compressed and stored in type-C tanks at approximately 18 bar. The company has adapted its land-based experience, particularly in waste-incinerator applications, into a maritime CCS solution.



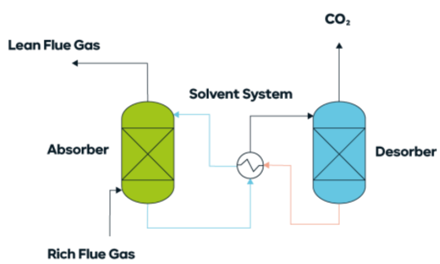


Figure 15. Carbotreat system process

The technology is progressing through TRL 6 to 7 and is considered suitable for both retrofits and newbuilds. Carbotreat has partnered with CONOSHIP for small ships and VDL for larger vessels, and is currently piloting the system on an LNG carrier as part of the EverLoNG CCS initiative. Two additional shipboard demonstrators are planned. Commercial readiness is at CRL 5, supported by more than a decade of operational experience reclaiming amines in land-based systems. The company holds LR Approval in Principle.

Carbotreat requires electricity, heat and solvent to operate, producing CO_2 in gaseous or liquefied form depending on the vessel's configuration. Theoretical capture levels are up to 85%, influenced by available heat, exhaust gas temperature and solvent cycling efficiency. Typical electrical demand lies in the range of 200–250 kWh per tonne of CO_2 captured, depending on compressor, cooling and pump specifications. Storage is generally in liquefied form using cryogenic or pressurised tanks.

The system's limitations include significant spatial and weight requirements for CO_2 tanks, which can add up to 5000 tonnes of stored CO_2 depending on voyage duration. Placement of this storage must be carefully managed to avoid unfavourable impacts on trim and stability. Crew must perform daily inspections of the absorbent circuit and associated machinery, and periodic solvent reclaiming is required to maintain amine performance. Although robust and based on proven industrial principles, the system's capture efficiency and energy requirements can vary with changes in engine load and gas temperatures, requiring careful system integration and operational planning.

2.4.2.5 Erma First

Erma First uses a proprietary amine solvent to absorb CO_2 from the ship's flue gas within an absorber column. The CO_2-rich solvent is routed to a stripper where heat regenerates the amine and releases the captured CO_2. The gas is then liquefied and stored in cryogenic tanks onboard at temperatures between –25°C and –30°C. The process requires outlet-gas cooling to approximately 40°C and CO_2 liquefaction at 15 to 18 bar to ensure stable onboard storage. For a system with a capture capacity of 1,000 kg/h, the absorber unit is roughly 4 m in height with a diameter of about 2 m, while CO_2 stripping can be carried out within an expansion tank. The system components are shown in Figure 16.

Erma First is currently at TRL 6, with two pilot systems planned for installation with major shipping companies. The company has signed a letter of intent with Capital Gas and Babcock to install its CCS system on new large-scale CO_2 carriers, with the first delivery expected in 2026. Commercial readiness is at CRL 5, supported by R&D efforts that began three years ago. The system has obtained Approval in Principle from Lloyd's Register and DNV, confirming compliance with maritime safety and design requirements. Installation for retrofits generally requires 6–8 weeks in dry dock, and the system is suitable for both retrofits and newbuilds.

Operational parameters include electricity, heat and solvent as inputs, with CO_2 produced in gaseous or liquefied form at capture levels reaching up to 90%. Standard system configurations range from approximately 165 kg CO_2 per hour up to around 2,500 kg CO_2 per hour. Regeneration of the solvent requires approximately 2.7 GJ of steam per tonne of CO_2 captured, and additional energy is consumed during liquefaction and storage. Solvent degradation requires periodic amine top-ups, typically every two years, and routine maintenance is required to ensure reliability of the liquefaction equipment.

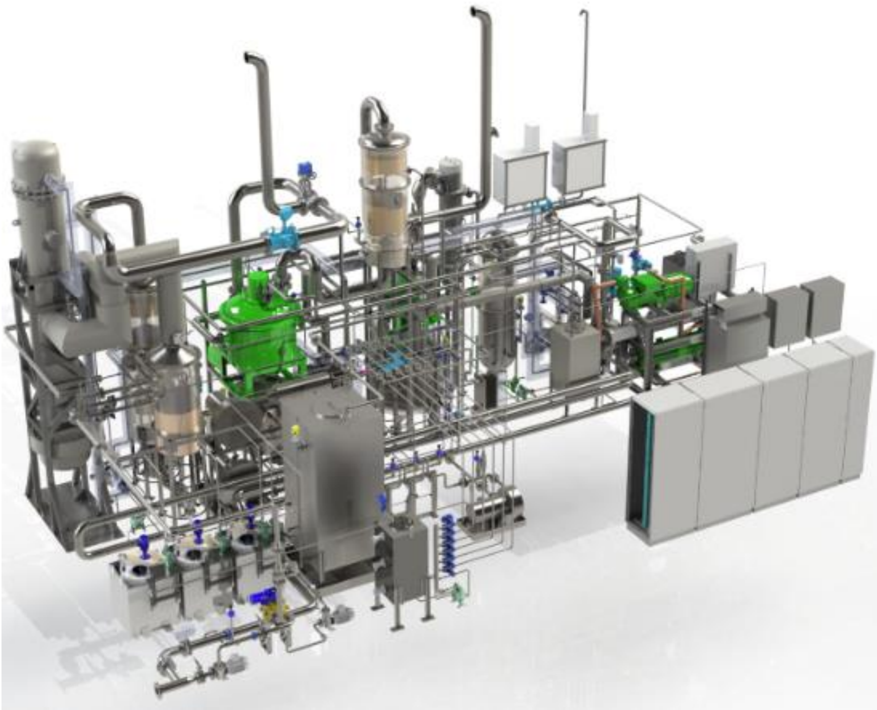


Figure 16. Erma First system concept design (Source: Erma First)

Limitations include the energy intensity of solvent regeneration and the added heat demand on the vessel's auxiliary systems. Liquefaction also imposes significant electrical load, making integration more challenging on ships with limited energy excess. Long-term effectiveness depends on the performance of the proprietary solvent, particularly under varying exhaust temperatures and fuel-type conditions.

2.4.2.6 Wärtsilä

Wärtsilä's CO_2 capture system uses a chemical absorption process in which exhaust gas contacts a solvent that selectively absorbs CO_2 as shown in Figure 17. The CO_2-rich solvent is pumped to a reboiler and heated, releasing the CO_2 and producing a regenerated solvent stream that is recirculated back to the absorber. Water vapour is condensed and removed prior to compression. The CO_2 gas is then dried, compressed and liquefied before storage in insulated tanks at about –26°C.

The company has achieved TRL 8, with the first installation scheduled on a Solvang LPG tanker in 2025. That system is projected to capture approximately 70% of the vessel's CO_2 emissions, storing the captured CO_2 in 360 m^3 tanks that provide 21 days of storage capacity. Wärtsilä has been developing carbon capture technology since 2019 and operates a dedicated test facility in Norway capturing up to 10 tonnes of CO_2 per day from a marine engine. Commercial readiness is at CRL 8, and the system will be available for maritime customers from 2026. DNV has granted Approval in Principle.

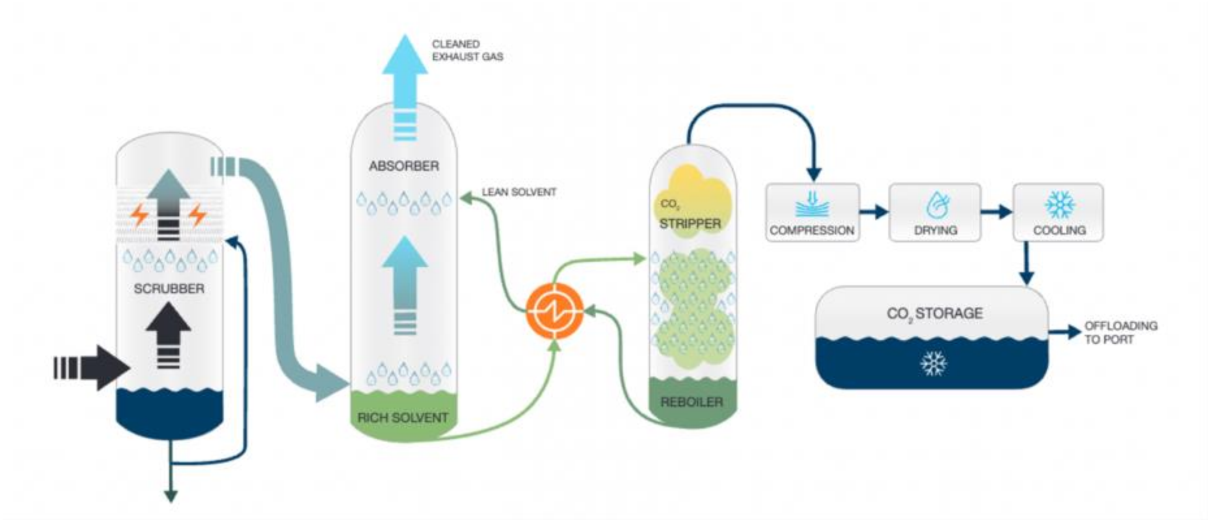


Figure 17. Wartsile Carbon capture process

Operationally, the system requires electricity, heat and solvent, and can achieve up to 70% capture efficiency in real operation. The CO_2 is stored in liquefied form, which requires additional compression and cooling equipment. Energy consumption, including steam demand for regeneration and power for liquefaction, creates a measurable parasitic load on the vessel. Solvent management is also an ongoing requirement, including periodic treatment, makeup solvent addition and regeneration processes.

Challenges include the significant energy requirement for solvent regeneration and CO_2 liquefaction, as well as the need for large CO_2 storage volumes on long voyages. Solvent availability, degradation and treatment are also key considerations, particularly as exhaust gas compositions vary by fuel type and engine settings.

2.4.2.7 CSSC 711

CSSC 711 uses a conventional amine-based chemical absorption process adapted for shipboard exhaust gas streams. Exhaust gas is channeled into the absorber, where CO_2 is captured by the solvent, and the CO_2-rich solution is transferred to a stripper column where heat regenerates the solvent and releases the captured gas. The CO_2 is liquefied and stored in Type-C pressurised tanks at around 10–15 bar and temperatures between –40°C and –25°C. At higher capture rates, additional pre-cooling is required to maintain liquefaction efficiency. Typical performance demonstrates capture rates of up to 80%, with energy demand of roughly 250 kWh per tonne of CO_2 captured and steam consumption of approximately 0.8 MT steam per MT of CO_2. The system components are illustrated in Figure 18.

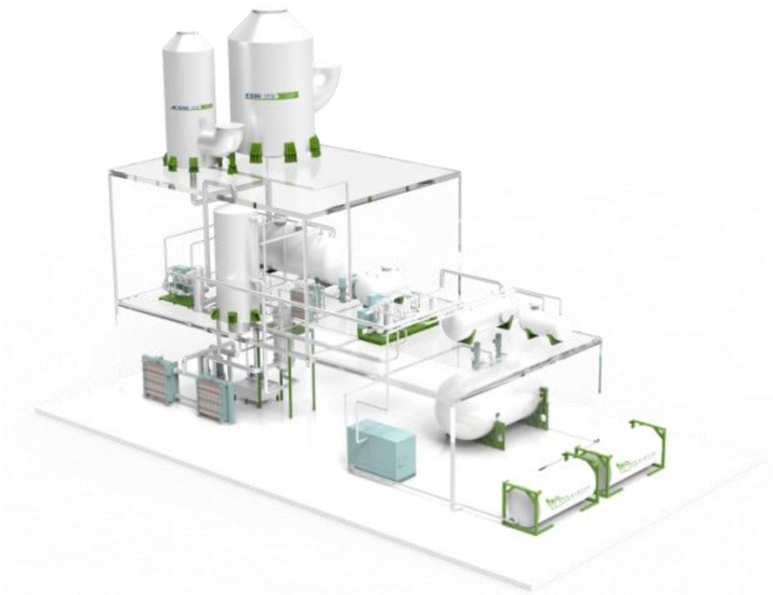


Figure 18. CSSC Carbon capture system (Source : CSSC)

The technology is at TRL 8 following installation on a 14,000 TEU Evergreen vessel, with class approval awarded by NK. At the commercial level, CSSC 711 is at CRL 8, reflecting design, testing and deployment of full commercial-scale units, including delivery of the first system for an 82,500 DWT bulk carrier and the first overseas offloading operation in the Port of Rotterdam. Offloading trials using standard port equipment have confirmed practical feasibility of handling liquefied CO_2 in a 20-foot containerised format. Installation typically follows a standard dry-dock schedule with supply periods of eight to ten months. The system has type approval or AIP from CCS, LR and DNV.

Operational inputs include electricity, heat and solvent, while the output is liquefied CO_2. The technology can be applied to both retrofits and newbuilds. Limitations include dependency on onboard power, freshwater and steam availability, particularly for ships operating outside Asia where service networks are less developed. Additional considerations include the vessel's electrical load margin and the need for reliable crew training to support system operation.

2.4.2.8 Sinotech

Sinotech's CCS process is structured into four stages. Exhaust gas is first cooled from roughly 300°C to 30°C, removing sulphur dioxide and particulates. The gas then enters an absorber where amine solvent selectively captures CO_2. Once saturated, the CO_2-rich solvent flows to a desorber where heat drives off the captured CO_2, which is subsequently compressed and cooled to between 2–4 MPa and –20°C for storage in Type-C tanks. The regenerated solvent is returned to the absorber, enabling continuous operation. This process is illustrated in Figure 19. Sinotech reports a capture efficiency of up to 90%, with CO_2 reductions of nearly 99.9% after liquefaction and purification.

The technology is at TRL 8, having completed Factory Acceptance Testing for a bulk carrier installation within a short delivery window. Commercial readiness is at CRL 7, supported by classification AIP certifications from ClassNK and LR. Sinotech debuted its system publicly at SMM 2022, followed by demonstrations and system optimisation, including weight reduction of 40% and energy savings of 10–15%. A second-generation system has been delivered and installed, with additional unit deliveries planned through 2025. Standard dry-dock periods apply for installation, and annual maintenance is required.

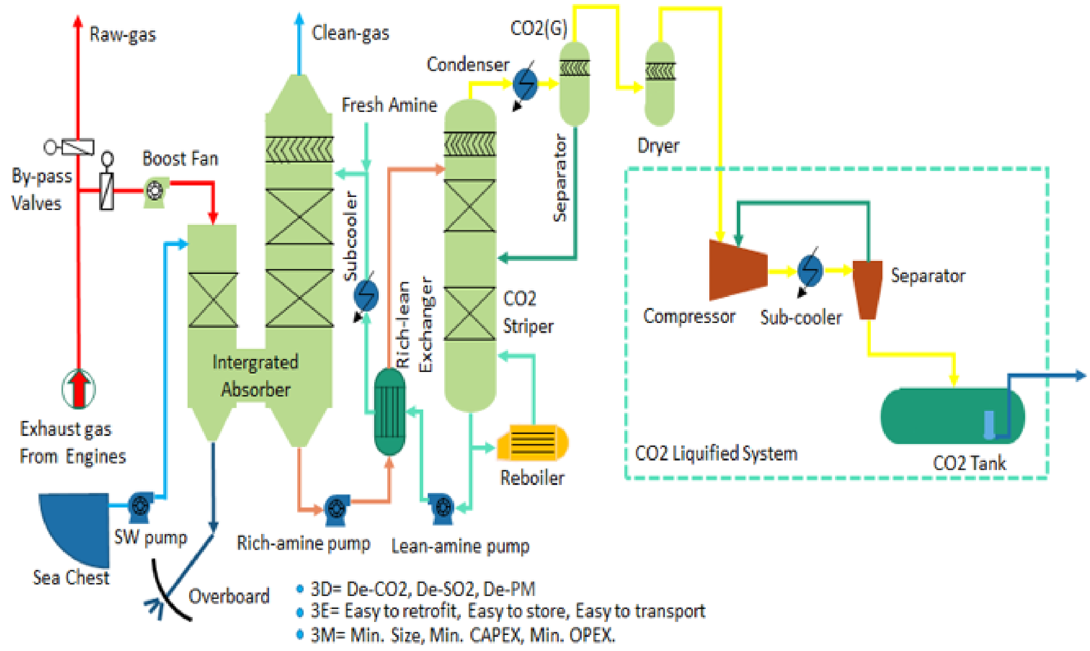


Figure 19. Sinotech Carbon Capture system process (Source: Sinotech)

The system requires electricity, heat and solvent as inputs, producing liquefied CO_2 for storage. Solvent use follows conventional absorption principles based on acid–base neutralisation. Liquefied CO_2 can be stored either in IMO Type C pressure vessels or in standard 20-foot and 40-foot tank containers. The use of tank containers is particularly advantageous for CCS installations on container vessels. The captured liquid CO_2 can be discharged in port to quayside tank trucks, dedicated CO_2 tank barges, or a permanent onshore reception facility. The optimal system configuration and the achievable CO_2 recovery rate, depend on several factors, including the vessel's operating route, available onboard storage capacity, and preferred discharge locations. Operational constraints include complex machinery requiring frequent inspection and the need for well-trained crews. As with several Asian-developed CCS solutions, the availability of service networks outside Asia may be an adoption barrier.

2.4.3 Membrane Separation

2.4.3.1 Compact Membrane Systems (Ardent)

Ardent's technology uses modular polymeric membranes to separate CO_2 from exhaust gas based on differential permeation rates. These membrane modules, as shown in Figure 20, allow varying levels of CO_2 enrichment, and the system can achieve up to 95% theoretical capture efficiency depending on membrane configuration and exhaust gas characteristics. Compared with solvent-based capture, membrane systems require less energy, particularly in the absence of solvent regeneration. Ardent reports that its membranes can reduce capture costs by up to 40% relative to solvent-based approaches, and a standard 40-foot containerised module can capture around 50,000 tonnes of CO_2 per year under suitable operating conditions.

The system is at TRL 6, supported by previous land-based installations with major industrial customers such as Chevron and OMV. However, maritime deployment has not yet been achieved, and the commercial readiness level remains at CRL 3 due to the absence of like-for-like marine demonstrations. Because membrane systems perform differently depending on engine exhaust composition, integration requires further validation under variable engine loads and exhaust temperatures. There are currently no class approvals, and no defined installation period, as marine demonstrations have not been undertaken.

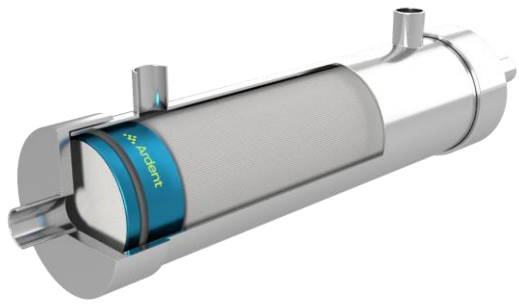


Figure 20. Ardent Membrane system

The system requires electricity to drive compressors and blowers, and the output is a concentrated CO_2 stream that may be stored either as gas or liquefied form depending on the vessel configuration. Limitations include sensitivity to impurities in exhaust gas, which can initially degrade membrane performance until stabilisation occurs. Maintenance requirements are higher than with solvent-based systems due to membrane replacement intervals, and operational uncertainties remain regarding integration with internal combustion engines. Without onboard liquefaction, additional systems must be installed to handle CO_2 storage, further complicating overall integration.

2.4.4 Cryogenic Separation

2.4.4.1 PMW Technology

PMW Technology applies a cryogenic separation method in which CO_2 is captured by freezing it onto 2 mm steel beads at extremely low temperatures, typically between –100°C and –70°C. Once bonded to the beads, the solid CO_2 is transferred to storage tanks using a scrubber heat exchange system. The process is highly automated and relies on a moving bed reactor design, where steel beads continuously circulate between freezing and regeneration zones. The process is illustrated in Figure 21. The captured CO_2 is later melted and stored in liquefied form. The system can withstand harsh engine conditions, with exhaust temperatures up to 460°C in normal operation and up to 600°C during transient bypass modes. The cryogenic separation process inherently delivers extremely pure liquid carbon dioxide, meeting the requirements of geological storage and reuse processes without further treatment.

PMW is at TRL 6, having demonstrated feasibility in land-based tests and validated scalability for small and medium-scale capture systems. Trials indicate potential applicability for marine engines, but the system remains at CRL 4 as it has not yet been deployed offshore. AIPs with DNV are in progress, and installation timelines are still being defined. The technology is adaptable to different vessel sizes, although high-flow trials above approximately 200 kg/h have not yet been completed, limiting full scalability validation.

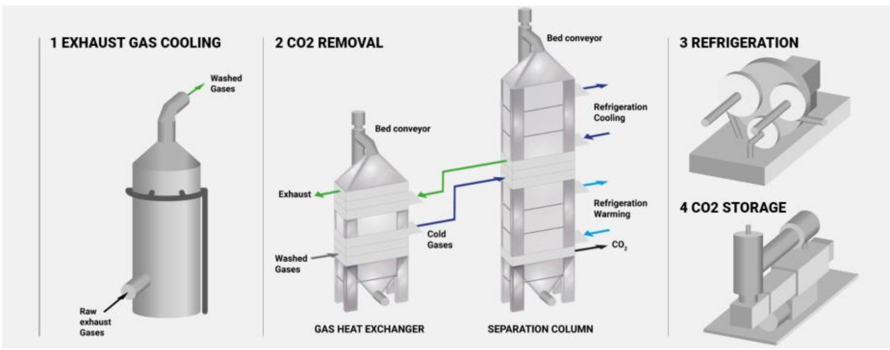


Figure 21. PMW Cryogenic Separation Process Outline

Operational inputs include electricity, heat and metal beads acting as the refrigerant medium. The system can theoretically achieve capture rates of up to 95%. Challenges include the need for bead replacement due to wear, which introduces a regular maintenance requirement. Current designs approach ambient pressure limits, and engineering refinements are ongoing to improve the pressure range and extend operational capability. The system also requires large electrical loads for cryogenic cooling and may need multiple modules for vessels with high exhaust-gas flow. Despite these challenges, studies indicate that larger-scale installations of up to 12,000 kW engine loads may be feasible in future commercial versions.

2.4.5 Calcium Looping

2.4.5.1 Seabound

Seabound uses a solid sorbent process based on calcium oxide (CaO) reacting with CO_2 in the exhaust gas stream to form calcium carbonate ($CaCO_3$). The system circulates CaO pebbles through the capture reactor, allowing them to bind CO_2 and convert into $CaCO_3$ as shown in Figure 22. The carbonated pebbles are pneumatically conveyed into sealed containers for storage and offloading at port. Seabound highlights that $CaCO_3$ can potentially be sold as a usable construction material, helping to offset operating costs. The process contains no hazardous chemicals and requires minimal specialised crew training.

The technology is at TRL 7, with the first system installed aboard a 3,200 TEU Lomar Shipping vessel under ABS Approval in Principle. The first installation achieved approximately 1.0 MT CO_2 per day capture over 100 hours of operation. Commercial readiness is now assessed at CRL 7–8, following the completion of Seabound's first full-scale commercial OCCS units in 2025–2026 and their deployment on the UBC Cork cement carrier. The company has transitioned from prototype demonstrations to market-ready hardware, supported by new commercial partnerships (Hartmann Group, Heidelberg Materials, ESA, ThyssenKrupp Polysius) and a production pipeline for 2026 deliveries. Installation fits within a standard 2–3 week dry-dock schedule. (Seabound, 2025)

Figure 22. Seabound Calcium Looping system (Source: Seabound)

Operational inputs include energy, heat and the initial CaO sorbent. The system can reach capture efficiencies of up to 80% in trials, although long-term performance depends heavily on impurity levels in exhaust gas, which can cause temporary reduction in capture efficiency before stabilisation. Storage requires significant onboard space because $CaCO_3$ is a solid bulk material, and each 20-foot container weighs roughly 28 tonnes when full. Seabound's approach requires swapping full containers at port, meaning that onboard arrangement and port logistics must be planned carefully. Long voyages require large numbers of containers, affecting deck space, weight distribution and operational efficiency. It is noted that $CaCO_3$ Mineralisation method from Seabound has been awarded an AIP from LR.

2.5 Vessel Segments Assessment

This chapter provides a high-level evaluation of carbon capture and storage (CCS) technologies for four representative vessel types: oil/chemical tankers, bulk carriers, container ships, and LNG carriers. The current body of literature offers limited insight into the comparative applicability of CCS across different ship categories. Most available studies examine individual CCS technologies in isolation or focus on a single vessel type, resulting in a fragmented evidence base.

Against this background, the following assessment consolidates relevant technical and operational insights to establish a clearer understanding of how vessel design characteristics influence the feasibility of onboard CCS integration. The analysis considers factors such as machinery arrangements, power availability, space and weight constraints, waste-heat recovery potential, operational profiles, and cargo-handling requirements. By aligning these vessel-specific attributes with the capabilities and limitations of current CCS technologies, the section highlights practical considerations that determine the suitability and integration potential of carbon capture systems across the four selected vessel types.

2.5.1 Tankers

Oil and chemical tankers offer comparatively favourable conditions for integrating onboard carbon-capture systems (OCCS), largely due to their machinery configuration, thermal characteristics, and established cargo-handling practices. Across larger segments such as VLCCs and Suezmax tankers typically provide sufficient deck area to accommodate LCO_2 storage tanks, absorbers, compressors, and associated equipment. However, integration must account for the fact that tanker decks are densely populated with cargo lines, vent masts, inert-gas piping, firefighting systems and safety-critical equipment, all of which complicate the routing of CCS modules and utilities. On smaller product carriers, chemical tankers and MR tankers, deck margins and freeboard are more limited, restricting equipment placement. Nevertheless, the shorter voyage durations typical of these trades reduce required onboard CO_2 endurance and can partly offset spatial constraints.

Thermal energy availability remains one of the strongest enablers in the tanker segment. Oil and chemical tankers operate large auxiliary boilers and steam systems for cargo heating, tank cleaning and pumping operations, generating substantial waste heat that can be redirected to meet the regeneration load of amine-based or solid-sorbent systems. Larger tankers with main-engine economisers benefit from additional hot-water and steam generation capacity, further reducing the burden on dedicated heating systems and lowering the overall integration challenge.

Effluent and by-product management is also aligned with established tanker operations. Crews are routinely trained in the handling of hazardous liquids, segregated tank systems and spill-prevention measures, which facilitates the safe management of solvent-rich effluents or aqueous amine–CO_2 mixtures generated by certain OCCS configurations. Importantly, tankers' operational routines, including cargo-handling procedures, terminal operations and ship-to-ship (STS) transfers, translate well to the handling and offloading of captured CO_2. Some vessels can repurpose existing slop tanks under ambient pressure/temperature conditions or allocate part of a cargo tank temporarily for intermediate CO_2 containment under defined operating conditions, reducing reliance on dedicated storage infrastructure during early deployment phases.

The increasing uptake of LNG-fuelled tankers introduces additional integration benefits. Dual-fuel machinery produces cleaner exhaust streams with lower particulate, sulphur and acid-forming components, reducing pre-treatment demands and improving the performance of amine-based systems. These vessels also typically feature more stable and higher-quality waste-heat profiles, especially where hybrid electric or combined-cycle auxiliary systems are employed. LNG propulsion also creates opportunities for pre-combustion pathways, although these technologies remain at moderate TRL.

Integration challenges remain. Deck-mounted LCO_2 tanks can affect trim, stability and GM margins, particularly on chemical tankers with limited stability envelopes. Hazardous-area zoning around manifolds and deck pipelines restricts permissible locations for compressors, electrical cabinets and rotating equipment. For long-haul crude trades, CO_2 storage volumes become significant, requiring large deck tanks or frequent offloading, while the availability of port-side CO_2 reception remains uneven across major tanker routes, constraining operational flexibility.

Overall, oil and chemical tankers retain a comparatively strong suitability for OCCS deployment. Their propulsion and cargo-handling systems, waste-heat availability, and crew expertise in managing hazardous fluids provide a solid foundation for integration. Provided that port-side CO_2 reception capabilities and regulatory frameworks develop in parallel, the tanker segment is positioned to become one of the early large-scale adopters of onboard carbon-capture technologies.

2.5.2 Bulk Carriers

Bulk carriers generally present less favourable conditions for onboard carbon capture system (OCCS) installation primarily due to deck-space constraints, limited waste-heat availability, and operational practices that do not naturally align with CCS effluent management. These constraints are more pronounced in the Handysize, Supramax and Panamax segments, where hatch-cover geometry, crane foundations and conveyor systems occupy the majority of the upper deck. Even on Kamsarmax and some Capesize vessels, the available deck footprint is restricted by cargo-handling equipment, leaving little uninterrupted space for LCO_2 tanks or modular capture units. Bulk carriers are among the vessel classes with the lowest structural flexibility for deck-mounted CCS installations due to their wide hatch openings and extensive cargo-gear footprints.

Waste heat availability is another limiting factor. Most bulk carriers operate with a single exhaust gas economiser (EGE) sized only for routine hotel-load steam demand. Unlike tankers, they generally lack auxiliary boilers or dedicated steam systems capable of supplying the regeneration duty required for amine-based CCS technologies. Bulk carriers are identified as one of the vessel categories with insufficient waste-heat recovery potential, noting that any shortfall would need to be met through additional equipment such as fired heaters or upgraded EGEs, both of which introduce material CAPEX and space penalties. This makes traditional solvent-based CCS systems challenging to integrate without significant modification of the energy system.

Effluent management presents further challenges. CCS configurations using amines or solid sorbents produce solvent-rich waste streams or aqueous CO_2-amine mixtures requiring controlled containment and specialised handling protocols. Unlike tankers, bulk carriers and their crews have limited familiarity with hazardous-liquid management, as their operational focus is on dry cargo and mechanical systems rather than fluid-handling operations. Introducing such effluent-handling procedures would require new storage tanks, transfer lines, spill-management systems and crew certification, substantially increasing both complexity and operational risk. This sensitivity to operational disruption is identified as a key barrier for the wider uptake of CCS in the bulk segment.

LNG compatibility also remains constrained. LNG-fuelled bulk carriers represent only a small portion of the global fleet, and the integration of Type-C LNG tanks, vapour-handling systems and safety zones already occupies much of the available upper-deck area. EMSA highlights that LNG-fuelled bulker designs have little additional space to support CCS modules, particularly for high-volume LCO_2 storage. Furthermore, pre-combustion pathways such as methane pyrolysis or LNG reforming remain at TRL 5–7 and are not yet mature enough for bulk carrier integration. As a result, LNG propulsion does not currently provide the same CCS-integration benefits observed in other segments, such as LNG-fuelled tankers or container vessels.

Overall, bulk carriers face significant technical and operational constraints for OCCS integration relative to other vessel classes. Limited deck availability, insufficient waste-heat resources, unfamiliarity with hazardous-liquid handling, and low LNG penetration collectively restrict the feasibility of conventional amine-based capture systems. In addition to these structural limitations, the operational profile of most bulk carriers, characterised by long-haul voyages, variable routing, and irregular port-call patterns, creates substantial endurance requirements for onboard CO_2 storage. These long voyage durations increase the volume of LCO_2 that must be carried between discharge opportunities, intensifying deck-space pressures and making integration more complex than in liner-type trades with predictable port intervals. Although pilot-scale installations may be feasible on larger Capesize vessels with more favourable machinery arrangements, fleet-wide adoption remains unlikely without major design modifications or technological advances that substantially reduce energy and space requirements. A partial exception exists for smaller bulkers, such as dedicated cement carriers or short-sea dry-bulk vessels, which operate on regular port schedules and may therefore be suitable candidates for alternative capture approaches such as calcium-looping, where captured CO_2 is mineralised as $CaCO_3$ and handled through existing bulk-cargo or ISO-container logistics. These niche opportunities, however, do not offset the broader structural and operational barriers that currently limit the sector's near-term suitability for large-scale OCCS deployment.

2.5.3 Containerships

Containerships present a unique integration profile for onboard carbon capture, with the primary constraint being the trade-off between CCS equipment footprint and revenue-generating TEU capacity. Installing LCO_2 pressure tanks or large capture modules would directly displace container slots and therefore affect commercial performance, particularly on feeder, Panamax and Neo-Panamax designs with limited deck and bay flexibility. Nevertheless, containerships benefit from frequent and regular port calls, which reduce endurance requirements for CO_2 storage. This operational pattern enables a shift towards modular, container-based storage options, including ISO tank containers for LCO_2 or containerised solids-handling units for alternative capture pathways.

Waste-heat availability is comparatively favourable. Containerships operate at higher continuous propulsion loads and higher service speeds than bulkers or tankers, resulting in substantial thermal output from the main engine and exhaust-gas economisers. In addition, large auxiliary generator sets are installed to power reefer containers, providing further recoverable waste-heat streams. EMSA identifies containerships as among the vessel types with the strongest thermal inventory for solvent-based OCCS systems, as their propulsion profile and auxiliary load enable more stable and predictable waste-heat recovery. This makes them well-suited to amine-based absorption or solid-sorbent adsorption systems that require consistent regeneration duty.

Effluent management poses fewer challenges compared with bulk carriers. The modular and containerised nature of containership logistics facilitates the use of ISO tank containers for intermediate effluent storage, simplifying handling requirements and reducing the need for deck-integrated effluent tanks. Regular port calls also permit predictable disposal or regeneration cycles, minimising operational complexity. Containership crews are generally familiar with handling containerised dangerous goods under IMDG protocols, making the introduction of CCS-related effluent handling comparatively manageable relative to other dry-cargo sectors.

LNG compatibility is increasingly relevant. The containership newbuild market has seen the fastest adoption rate of dual-fuel LNG engines globally, driven by emissions regulations and liner-company decarbonisation strategies. LNG-fuelled containerships offer exhaust streams with lower particulates and sulphur content, reducing pre-treatment burdens for post-combustion systems. They also support potential synergies with cryogenic CO_2 capture, membrane-based techniques, and emerging pre-combustion pathways such as LNG-to-hydrogen concepts.

Calcium looping ($CaCO_3$-based) solid-mineralisation systems represent a particularly promising option for containerships. These systems capture CO_2 by converting it into stable solid $CaCO_3$ onboard, eliminating the need for cryogenic storage and pressure vessels. Because both $CaCO_3$ product and fresh CaO can be stored and handled within standard ISO containers, calcium looping integrates naturally with container-ship cargo operations, avoiding permanent deck-space penalties. Frequent port calls allow regular discharge of $CaCO_3$ and replenishment of CaO, aligning well with shore-side regeneration cycles and reducing endurance constraints. This combination of container-compatible storage, minimal structural modification, and alignment with operational patterns makes calcium looping one of the most practicable CCS approaches for this vessel type, particularly in short-sea and liner trades with dense port networks.

Overall, containerships present a mixed but promising CCS integration landscape. The primary constraint is the commercial cost of lost TEU capacity; however, strong waste-heat availability, compatibility with ISO-container-based storage, frequent port calls, and growing LNG penetration support favourable conditions for OCCS deployment, particularly in trades where endurance requirements are low and regular offloading cycles are feasible.

2.5.4 LNG Carriers

LNG carriers present some of the most favourable technical conditions for integrating onboard carbon capture systems (OCCS), primarily due to their machinery arrangements, exhaust characteristics, cryogenic infrastructure and operational culture. Although deck space is partially constrained by the large Type-C or membrane cargo containment systems, the installation of LCO_2 storage tanks remains feasible when appropriate design trade-offs are applied. Unlike containerships or tankers, deck arrangements on LNG carriers typically include defined service areas around the cargo system and machinery spaces that can accommodate pressure vessels or process modules with limited structural intervention. Moreover, LNG combustion produces significantly cleaner exhaust streams with low sulphur, particulate and acid-forming contaminants, reducing pre-treatment requirements and solvent degradation rates. This enhances the efficiency and operational stability of post-combustion absorption and adsorption systems.

Waste-heat recovery potential is substantial. LNG carriers operate with high thermal loads due to cargo handling, reliquefaction systems, and propulsion arrangements. These vessels are equipped with robust steam systems, auxiliary boilers and exhaust-gas economisers capable of supplying a stable thermal inventory well suited to the regeneration duty of amine-based CCS systems. Additionally, LNG carriers possess abundant “cold energy” associated with LNG cargo conditioning and boil-off gas management. This cold energy can be harnessed for cryogenic CO_2 capture, condensation and partial liquefaction, reducing energy demand and offering integration synergies not available on conventional petroleum or dry-cargo ships. LNG carriers form one of the vessel types with the greatest potential for hybrid thermal–cryogenic CCS configurations.

Effluent handling readiness is also strong. LNG carriers have an established operational culture centred around cryogenic fluids, hazardous-area zoning, high-purity gas systems and rigorous safety protocols. This means that integrating CCS-related effluent containment, solvent-handling systems or additional cryogenic lines fits naturally within existing onboard practices. Crew familiarity with complex fluid management, redundant safety controls and leak-detection systems provides a strong baseline for managing CO_2 streams or solvent-rich by-products. Adequate power margins and auxiliary system capacity further support CCS integration without requiring major redesign of the vessel’s utility network.

LNG compatibility is inherently high. LNG carriers already operate extensive cryogenic systems, reliquefaction equipment and insulated piping, making them well aligned with CCS technologies that involve low-temperature CO_2 conditioning, partial liquefaction or cryogenic purification. This existing infrastructure reduces the incremental integration burden and supports the deployment of both post-combustion and cryogenic capture routes. In addition, emerging pre-combustion technologies, such as methane pyrolysis (thermocatalytic decomposition) or autothermal reforming with onboard CO_2 capture, are conceptually compatible with LNG carriers due to the availability of high-purity methane and well-developed gas-handling architectures.

Taken together, these factors position LNG carriers as one of the most technically suitable vessel types for OCCS integration. Their clean exhaust, high and stable waste-heat output, mature cryogenic systems and operational familiarity with complex gas-handling processes significantly reduce integration barriers relative to other ship classes.

2.5.5 Concluding Remarks on Vessel Suitability

Across the major deep-sea vessel classes, the technical feasibility of onboard carbon capture varies widely due to fundamental differences in machinery configurations, operational patterns, and available installation space. LNG carriers and large crude carriers emerge as the most technically favourable platforms, supported by substantial waste-heat inventories, clean exhaust streams, and mature cryogenic-handling infrastructures that reduce integration complexity. Containerships face a clear commercial penalty in the form of TEU displacement, yet their strong thermal profiles, frequent port calls, and compatibility with modular ISO-based storage systems, including promising alternatives such as calcium-looping with containerised $CaCO_3$ handling, provide credible pathways for scalable deployment. Bulk carriers, by contrast, encounter more structural and operational barriers, particularly in terms of deck availability, limited waste heat and unfamiliarity with hazardous-liquid management, making CCS more challenging without significant design adaptation. These technical differences are already reflected in early market trends: containerships currently lead confirmed installations, as observed in Figure 23, LNG and gas carriers show growing uptake, and tanker adoption remains limited but gradually increasing as owners confront tightening EU ETS and anticipated carbon-cost exposure. Collectively, these patterns indicate that while CCS is technically viable across multiple vessel types, its near-term commercial diffusion will concentrate in segments where structural layouts, machinery systems, and operational cycles naturally align with the spatial, thermal, and logistical requirements of onboard carbon capture.

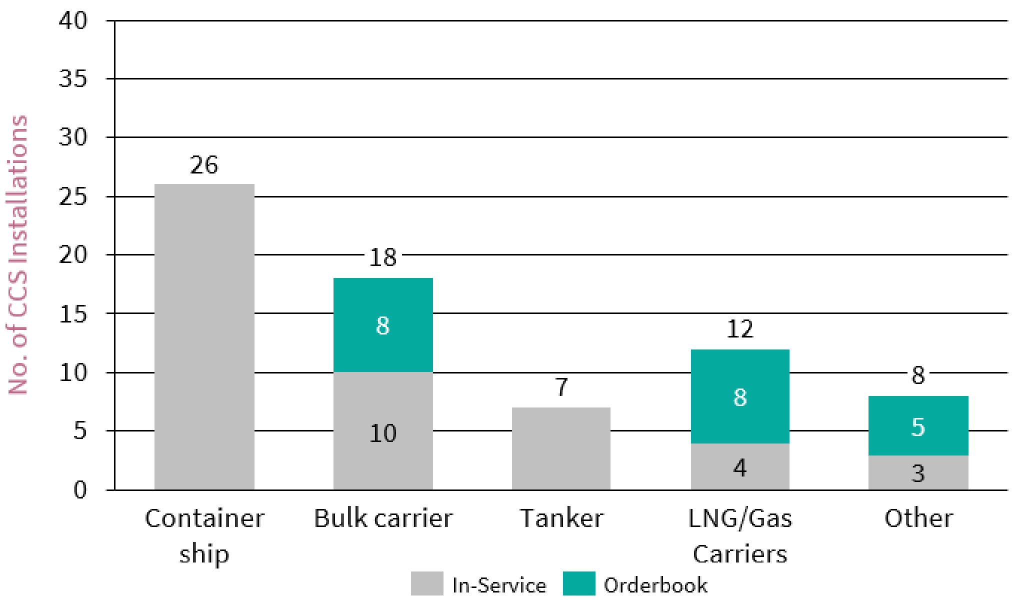


Figure 23. Number of OCCS installations per vessel segment (Clarksons, 2025)

Based on the above findings, a high-level feasibility assessment of each vessel type for the integration of CCS is presented in Table 3. The feasibility is evaluated considering technical and operational suitability of CCS on a comparative basis.

Table 3. Vessel segment feasibility analysis

Vessel Type	OCCS Feasibility	Key Considerations
Tanker	Medium - High	+ Thermal energy availability + Deck space availability, larger tankers have ample space - Potential cargo loss, cargo compatibility issues for chemical tankers
Bulk Carrier (general)	Medium - Low	+ Stable engine loads - Deck space availability, cargo loss/ cargo handling interference - Lower available power for OCCS - Limited crew experience chemical effluents handling
Containerships	Medium - High	+ Predictable and regular port calls + Containerised Calcium looping systems may be a particularly promising option - Cargo loss/interference
LNG carriers	High	+ High synergies with existing infrastructure, cryogenic systems etc + Low Pre- treatment requirements + Pre-Combustion technologies suitability - Limited Deck space availability

The OCCS technology suitability is also evaluated across vessel types based on a comparative basis in Table 4.

Adsorption Technology and Fuel Reforming have not been included, as their application has been considered of very low TRL level for onboard installations.

Table 4. OCCS Technology suitability by vessel type

OCCS Technology	Tanker	Bulk Carrier	Container	LNG Carrier	Key Considerations
Thermo-Catalytic Decomposition	Low	Low	Low	High	• More suitable for LNG carriers or gas-fuelled vessels where fuel availability and cryogenic infrastructure already exist. • Lab/pilot maturity only; no marine-ready systems; high energy & hydrogen integration challenges.
Chemical Absorption	High	Medium	Medium	High	• May use available steam/heat and integrates with existing auxiliaries on tankers • Requires heat and LCO_2 handling infrastructure • Heavily reliant on availability of shore side CO_2 facilities which may be a challenge for the tramp sector.
Membrane Separation	Medium	Medium	High	Medium	• Compact/Modular. No chemicals needed. Favourable for space-constrained bulkers and container vessels • Energy-intensive; limited marine demonstrations • Heavily reliant on availability of shore side CO_2 facilities which may be a challenge for the tramp sector.
Cryogenic Separation	Medium	Low	Low	High	• High synergy for LNG Carriers where cryogenic infrastructure already exist • Space and electrical demand limit feasibility on most bulk and container ships. • Heavily reliant on availability of shore side CO_2 facilities which may be a challenge for the tramp sector.
Calcium Looping	Medium	High	High	Medium	• High synergy for bulker and container vessels as solid product can be handled via existing infrastructure • Industrial maturity is higher, but shipboard integration is immature; mass penalty is high

Key takeaways from technology suitability across ship types can be summarised as follows:

- Chemical Absorption remains the most broadly deployable OCCS option, scoring High for tankers and LNG carriers and Medium for bulk and container ships. Its maturity and ability to use existing heat-integration pathways make it the most feasible near-term solution, but reliance on steam and the need for LCO_2 handling infrastructure may limit application on space-constrained ships.

- Membrane Separation may offer strong advantages for container vessels and bulk carriers due to its compact footprint and lack of chemical handling. However, the method's high electrical demand and limited marine demonstrations still constrain large-scale rollout.
- Cryogenic Separation is uniquely well-suited to LNG carriers, where cold-energy integration from LNG boil-off gas significantly lowers power demand. Outside the LNG segment, cryogenic systems face challenges due to high energy requirements and large equipment volume, making them less viable for bulk and container vessels.
- Calcium Looping stands out for bulk and container ship applications, mainly because the solid carbonate product can be integrated into existing cargo-handling or shoreside bulk material logistics. Despite this advantage, shipboard implementation remains immature, and the mass penalty of solids limits its feasibility on lightweight or volume-constrained vessels to achieve higher capture rates.
- Thermo-Catalytic Decomposition is only suitable for LNG or gas-fuelled vessels, where methane feedstock and cryogenic infrastructure are already present. TCD avoids LCO_2 storage entirely by producing solid carbon, but its low TRL, high-temperature reactors, and hydrogen-integration challenges make it impractical for tankers, bulkers, and container ships in the near term

2.6 Integration Challenges, Operational Impacts and Mitigation Measures

This section highlights the integration and operational challenges that affect the wider adoption of OCCS in the maritime industry.

2.6.1 Space, Weight, and Stability Impacts

Installing carbon capture and storage (CCS) systems onboard requires significant space and introduces substantial additional weight, both of which present key integration challenges. The added mass and its vertical and longitudinal distribution can materially affect the vessel's stability characteristics. A typical CCS installation includes absorber and stripper columns, CO_2 compression units, liquefaction systems, LCO_2 storage tanks, and associated auxiliary equipment, all of which demand considerable deck or machinery space.

Beyond footprint constraints, these components often increase the vessel's vertical centre of gravity (VCG), particularly when equipment is installed on upper decks or within funnel casings. An elevated VCG reduces the metacentric height (GM), potentially increasing roll motion sensitivity and affecting overall stability margins. Consequently, careful naval architectural assessment is required to ensure compliance with intact and damage stability criteria while maintaining acceptable seakeeping performance.

Onboard LCO_2 tanks

The required LCO_2 storage volume is strongly related to daily fuel consumption, gross capture rate, and endurance. Oil Tankers have an advantage compared to other vessel's types due to the extended upper deck space in way the cargo area. However, many vessel segments, especially geared bulk carriers, that have limited upper-deck spatial availability for large Type-C LCO_2tanks.

- Potential locations include the main deck (Tankers, LNG Carriers), aft cargo hold (Container/Feeder), or the uppermost deck (RoPax).
- Large Type-C tanks installed above deck elevate VCG.
- Final positioning depends on space availability, structural strength, and hazardous-area classification requirements.

- If located within a hazardous zone, additional safety measures such as dedicated ventilation, gas detection sensors, and explosion-proof equipment are required. All associated electrical and control equipment must be certified for explosive atmospheres.
- Mounting tanks above deck to avoid hazardous-area compliance is possible, but this requires additional structural reinforcement (up to ~10% added weight) and may influence overall stability.
- Retrofitted installations may require deck reinforcements or the relocation of existing equipment (e.g., bollards, foam monitors) to create the necessary footprint and ensure safe integration.

For a Kamsarmax bulk carrier consuming approximately 31 t/day MGO-equivalent fuel, the required LCO_2 storage volume increases quickly as capture rates rise, as shown in Table 5. Based on typical Type-C tank dimensions, capture rates above roughly 50% can demand such extensive deck area that main-deck installations become technically or operationally unfeasible.

Table 5. Required LCO_2 tank volume for 30 days of endurance.

Capture Rate Gross (%)	Low Pressure (m^3) Pressure: 5.7 bar to 10 bar Temperature: -54°C to -40°C LCO_2 Density: 1,145kg/m^3	Medium Pressure (m^3) Pressure: 14 bar to 19 bar Temperature: -30°C to -21°C LCO_2 Density: 1,055kg/m^3
10%	312	338
20%	623	676
30%	935	1014
40%	1246	1353
50%	1558	1691
60%	1869	2029
70%	2181	2367
80%	2492	2705
90%	2804	3043

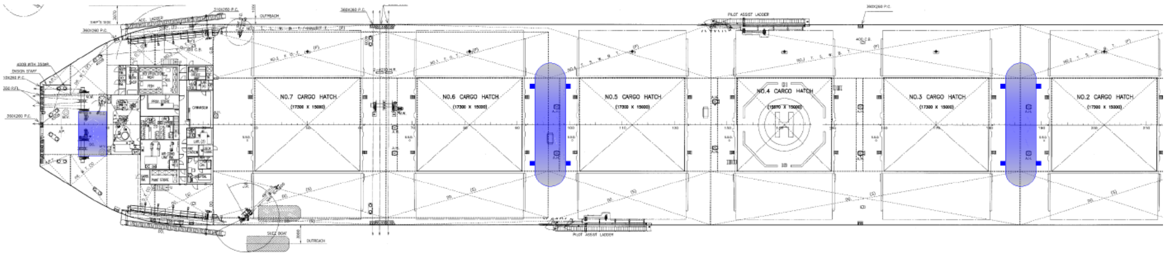


Figure 24. Potential LCO_2 tank installation locations on a bulk carrier

Potential LCO_2 tank locations are shown in Figure 24. Some challenges associated with this can be listed as:

- Tanks are located within the operational area of the cranes, potentially requiring a protective structures.
- Accessibility and maintenance in the areas adjacent to the tanks and cargo holds may be restricted
- Interference with cargo handling operations.

Liquefaction Plant

The CO_2 liquefaction unit is typically installed either adjacent to the engine room or within a designated deck area positioned close to the main capture equipment, ensuring short transfer distances and simplified system integration. Due to the presence of pressurised CO_2 and the associated risk of leakage, the liquefaction module must comply with safety standards equivalent to those applied to LCO_2 storage tanks, including robust ventilation arrangements, continuous gas-detection systems, and the use of explosion-proof electrical equipment. To meet these requirements, the unit is often housed within a segregated, purpose-built compartment located beside or outside the engine room rather than within the general machinery space, thereby reducing risk exposure and supporting safe operation.

Calcium carbonate storage

In calcium looping, calcium carbonate ($CaCO_3$) is typically the final product because it is stable and easy to manage. The process is governed by a straightforward reaction in which CO_2 combines with calcium oxide (CaO) and water to form $CaCO_3$. Stoichiometrically, one mole of CO_2 produces one mole of $CaCO_3$. With molar masses of 44 g/mol for CO_2 and 100 g/mol for $CaCO_3$, this results in a mass conversion ratio of roughly 2.27:1. Consequently, mineralizing 1 tonne of CO_2 yields approximately 2.27 tonnes of $CaCO_3$.

This conversion factor is critical when estimating material outputs, as it directly influences the storage, transport, and potential reuse requirements for the solid mineralised product.

2.6.1.1 Mitigation Measures – Newbuild and Retrofit cases

The integration of LCO_2 storage associated with OCCS systems introduces substantial spatial, structural, and stability challenges. These challenges arise primarily from the significant volume required to store captured CO_2 over typical voyage durations, as well as the additional weight and its vertical and longitudinal distribution within the vessel. For long-haul vessels in particular, storage capacity rather than capture efficiency often becomes the principal limiting factor. Mitigation of these constraints therefore requires early design consideration, operational optimisation, and alignment with broader decarbonisation strategies.

For newbuilding vessels, the most effective mitigation pathway is integration at the concept and basic design stages. When LCO_2 storage is considered from the outset, structural reinforcement, deck load capacity, longitudinal strength distribution, and stability margins can be dimensioned accordingly. Hazardous area zoning, vent mast arrangements, and segregation distances can also be incorporated into the general arrangement without later compromise. Although weather-deck Type-C cylindrical tanks remain the most mature and technically straightforward solution, early design integration enables more innovative configurations to be assessed. These may include hull-integrated tanks within widened void spaces, partially recessed "CO_2 well" installations to lower the vertical centre of gravity (VCG), or relocation of the accommodation block forward to release space above the engine room. Hybrid arrangements combining deck-mounted and partially integrated tanks may also offer improved weight distribution and stability performance. Such solutions allow more effective management of VCG, metacentric height (GM), trim, and longitudinal bending moments, while preserving cargo functionality.

In practice, however, shipyards currently have limited standardised designs for such configurations and are generally cautious about committing significant engineering resources without firm commercial incentives or regulatory certainty. As a result, fully optimised OCCS-integrated hull forms remain largely bespoke and project-specific. A realistic transitional strategy is therefore the implementation of "OCCS-ready" design provisions. Under this approach, vessels are constructed with reserved deck space, structural reinforcement in designated tank zones, pre-assessed intact and damage stability margins accounting for future CO_2 mass, and sufficient electrical power margins for compression and liquefaction systems. Routing corridors for future piping and trunking may also be pre-planned. This strategy preserves future retrofit flexibility while avoiding immediate capital expenditure and reduces technical risk when regulatory or commercial drivers materialise.

In parallel, the integration of Energy Efficiency Technologies (EETs) offers a complementary mitigation pathway. Because onboard storage requirements scale directly with CO_2 generation, reductions in fuel consumption proportionally reduce required LCO_2 tank capacity. Even modest efficiency gains of 10–15% can materially decrease storage volume, structural load, and deck footprint requirements. Relevant measures include waste heat recovery systems, shaft generators, hull form optimisation, air lubrication systems, wind-assisted propulsion technologies, and operational measures such as trim and speed optimisation. When combined with OCCS, these technologies reduce both emissions and storage burdens, improving overall system feasibility.

Operational profile plays an equally critical role. Vessels operating short-haul routes or within defined trading corridors require lower endurance storage capacity and can therefore accommodate higher capture rates without excessive tank volume. In contrast, long-haul tramp operations may necessitate moderated capture rates or variable capture strategies to avoid impractically large storage installations. The development of Green Corridors, where capture, temporary storage, offloading, and permanent sequestration infrastructure are coordinated, may further enhance viability by reducing storage duration requirements and enabling predictable discharge cycles.

The measures described above, such as implementing EETs and focusing on short, route-specific trades, can also help mitigate the challenges of retrofitting existing vessels. Nevertheless, some ship types face pronounced spatial constraints, with Bulk Carriers, particularly geared ones, being a notable example.

For vessels already in operation, feasibility assessments are essential to identify space limitations and determine whether CO_2 capture and storage systems can be realistically integrated. For new acquisitions, a focused checklist of key layout requirements, such as available cross-deck width and length, non-folding hatch covers, aft-deck arrangements, and the position of free-fall lifeboats, can support informed commercial decision-making.

Ultimately, effective mitigation of CCS components and LCO_2 storage constraints requires a systems-level approach integrating naval architecture, machinery design, operational planning, and infrastructure alignment. Early-stage design integration provides the greatest flexibility for newbuild vessels, while

OCCS-ready provisions and operational optimisation represent pragmatic interim solutions for the existing fleet. The balance between capture rate ambition and practical storage feasibility will remain a central design trade-off in the deployment of onboard carbon capture systems.

2.6.2 Energy Demand

The energy penalty of OCCS refers to the additional thermal and electrical power required to capture, process, liquefy, and store CO_2 onboard. This significant parasitic load reduces overall vessel energy efficiency, increases fuel consumption, and may partially offset the emissions reduction achieved through capture. The energy penalty associated with OCCS varies widely depending on the capture technology, capture rates, operating conditions, and system configuration. Higher generator utilisation to cover these parasitic loads also leads to increased maintenance costs for the owner due to additional running hours, shorter service intervals, and increased spare-parts demand

Among the available options, chemical absorption systems remain the most commercially mature as discussed in Section 2.2; however, they are also among the most energy-intensive. In these systems, the primary energy burden stems from the heat required for solvent regeneration depending on the solvent formulation and process design. In addition to the thermal load, substantial electrical power is required to operate pumps, blowers, fans, and CO_2 compression equipment. When the total heat and electrical demands are converted into fuel consumption equivalent, feasibility studies report fuel penalties in the range of 9% to 30% depending on the capture rates.

Membrane-based CO_2 separation systems also impose notable energy penalties. Feasibility studies indicate fuel penalties of around 15%. As these systems rely almost entirely on electrical power rather than thermal energy, they place additional strain on the vessel's auxiliary generators—an issue that is particularly challenging for smaller ships with limited electrical margins. Furthermore, the energy penalty increases as capture rates rise, since higher CO_2 recovery requires greater pressure differentials and larger membrane surface areas, compounding electrical consumption and operational load.

Cryogenic systems are among the most energy-intensive options due to due to the low CO_2 concentration in marine exhaust and high refrigeration loads. The energy penalty for cryogenic systems varies significantly depending on whether the system is "standalone" or "integrated" with other onboard systems on LNG fuelled vessels. On integrated systems vessels fuelled by LNG, the "cold energy" released during fuel regasification can be used to provide the necessary cooling. In these cases, the energy penalty is predicted to be below 10%. For conventional fuel-oil ships without a "cold" source, the penalty is higher, often ranging between 15% and 30%. This is primarily due to the power required for large refrigeration compressors.

The energy penalty for calcium looping (mineralisation) systems is generally lower than that of chemical absorption because it avoids the high thermal energy required for solvent regeneration. The fuel penalty for mineralisation OCCS is estimated to be approximately 7% to 12% depending on the specific integration and vessel type. The primary energy consumption in mineralisation comes from the mechanical handling of solids (limestone pebbles/powder), flue gas fans to overcome pressure drops, and any pre-treatment of the exhaust gas. If a regenerative calcium looping concept is applied, an additional shore-side energy demand is required to regenerate the spent sorbent (Calcium Carbonate) back into active material (Calcium Oxide) through high-temperature calcination (≈900–950 °C). This step introduces a significant shore-side fuel or electricity demand, comparable to conventional lime production processes.

2.6.2.1 Mitigation Measures – Newbuild and Retrofit cases

For newbuild vessels, managing the additional electrical demand from OCCS is considerably easier especially when the ship is designed from the outset as OCCS-ready. In such cases, the parasitic load under different operating conditions can be evaluated during the design phase and incorporated into the vessel's electrical balance. This allows diesel generators and auxiliary systems to be sized optimally. It also enables seamless integration of a shaft generator early in the design process, rather than adding one later as a retrofit.

A correctly dimensioned shaft generator can supply a substantial portion of the OCCS power demand, thereby reducing additional fuel consumption and limiting the impact on the net capture rate. Its sizing is closely tied to the selected main engine power rating and corresponding load-curve characteristics. Ideally, the propulsion and electrical systems should be configured so that diesel generators are not required during normal sea-going operation. This arrangement lowers overall costs, reduces system complexity, and improves operational robustness.

Determining the optimal configuration requires further analysis, considering factors such as the vessel's operating profile, integration of waste-heat recovery for electrical production or HVAC loads, and the use of variable-frequency drives (VFDs). These elements form an important design trade-off that must be evaluated during concept development and detailed engineering.

A detailed feasibility assessment is recommended to evaluate whether a shaft generator (Power Take-Off, PTO) can be installed to partially relieve the auxiliary engines and, where possible, support single-generator operation during normal sea-going conditions. However, adding a shaft generator as a retrofit is an invasive and technically demanding modification. Its suitability depends heavily on available space, the configuration of the main engine, and the margins within the engine's load diagram. Because of its high capital cost (CAPEX), this solution is best suited to newbuild or relatively young vessels, typically under five years old, so that the investment can be recovered within the remaining operational life of the ship. Even if an immediate OCCS installation is not planned, installing a shaft generator may still be worthwhile as a future-readiness measure that enhances overall energy performance.

The potential to integrate waste-heat recovery (WHR) systems should also be explored. WHR technologies capture heat from existing sources, such as main engine jacket water or exhaust steam, to produce electrical power or cooling capacity for HVAC systems. As a standalone retrofit, WHR systems generally offer payback periods of 3–5 years. When an OCCS is later added, the recovered steam is redirected to process heating rather than electricity generation; while WHR alone cannot eliminate the need for operating a second generator during OCCS operation, it still contributes meaningfully to reducing overall fuel consumption and associated emissions. Similar to shaft generator retrofits, WHR integration can be justified even without a confirmed OCCS installation, as it improves long-term vessel efficiency and reduces carbon intensity.

Technology providers can also provide specific strategies to reduce additional energy demand. In amine-based OCCS systems, the Stripper unit, where the solvent is heated for regeneration, represents the largest thermal load. It is therefore essential for technology providers to evaluate and propose effective energy-integration strategies that reduce this demand. Typical solutions involve the use of economizers and pre-heaters to capture and reuse waste heat. Sinotech, for example, employs a solvent heat exchanger that recovers heat directly from the exhaust stream, eliminating the need for steam as an intermediate source. This design achieves markedly lower parasitic energy consumption compared to other vendor offerings. Optimizing energy flows remains a key area for system improvement, providing substantial opportunities for tailoring performance and enhancing overall efficiency.

2.6.3 Safety Considerations

The integration of OCCS introduces new hazard profiles onboard vessels, combining high-pressure systems, cryogenic fluids, chemical solvents, rotating equipment, and confined space risks. The following subsections expand the key risk categories that must be addressed during system design, installation, and operation through formal HAZID, HAZOP, and class approval processes.

Asphyxiation Risks from CO_2 Leakage

Liquefied CO_2 poses a significant asphyxiation hazard if released into enclosed or partially enclosed vessel spaces. Even small leaks during compression, transfer, or storage can rapidly displace breathable air, creating life-threatening conditions for personnel. CO_2 is colourless and odourless, and because it is heavier than air, it accumulates in low-lying areas such as bilges and machinery-space recesses. Proper ventilation, continuous gas-detection systems, fail-safe isolation valves, and rigorous confinement design are essential to mitigate this risk.

Solvent Contamination (Chemical Absorption Systems)

In amine-based OCCS installations, contamination of the solvent system can introduce additional operational hazards. MEA solvents can degrade through interaction with engine exhaust contaminants, including SO_x, NO_x, particulate matter and metal ions, resulting in corrosive by-products that must be safely managed. Contaminated solvent can form nitrosamines and nitramines, compounds that are harmful if inhaled, ingested, or released into the marine environment. Dedicated solvent-preconditioning steps (e.g., bilge separation, heat recuperation, filtration) are required to prevent degradation and ensure safe handling.

Solvent Degradation and Hazardous Emissions

Degraded amine solvents may release harmful compounds when exposed to engine-exhaust temperatures. These emissions pose environmental and occupational hazards, requiring strict monitoring of solvent condition, emissions levels, and waste-disposal methods. Effective emission-control systems and regular solvent testing (e.g., to detect nitrosamine formation) must be integrated into the operational procedures to ensure safety and environmental compliance.

Crew Exposure to Solvents and CO_2

Operational tasks such as sampling, maintenance, or solvent replacement can expose crew members to hazardous chemicals. Chronic exposure to degraded amines, corrosion products, or concentrated CO_2 streams can result in respiratory, dermatological, or systemic health impacts. Proper PPE, closed-loop handling systems, strict maintenance protocols, and comprehensive crew training are critical to preventing occupational harm.

Equipment Compatibility and System Integration Risks

Mismatches between the capture unit, liquefaction module, and storage system can cause significant safety concerns, including unstable operating conditions, back-flow risks, or unexpected phase changes. Poorly integrated systems increase the likelihood of failure, such as heat-exchanger imbalance, compressor overload, or tank overfilling. CaO is caustic; contact with moisture forms alkaline slurries ($Ca(OH)_2$), causing corrosion/irritation risks and potential line plugging if water ingress occurs. Ensuring compatibility through system-level design, class-approved integration studies, and dynamic simulation during engineering phases is essential.

Pressure Control and Overpressure Failure

OCCS units contain multiple components operating under high pressure, such as compressors, liquefiers, stripping columns, and LCO_2 storage tanks. Malfunctioning pressure control systems or pressure-relief valves especially within the stripper column in solvent-based systems may lead to dangerous overpressure scenarios. Failure modes may include vessel rupture, pipeline failure, or rapid phase transition events (RPTs). Compliance with class rules, integration of dual-redundant pressure-relief devices, and stringent pressure-vessel certification are therefore mandatory.

Thermal Stress from Cryogenic CO_2 Handling

Cryogenic OCCS introduces extreme temperature differentials that can compromise material integrity. Inadequate design of the LCO_2 storage tank or associated piping may result in thermal cycling, embrittlement, or stress-induced cracking. Temperature-induced instabilities increase the likelihood of leakage, equipment failure, and even catastrophic tank breach. Proper material selection, insulation systems, fatigue analysis, and strict adherence to cryogenic safety guidelines are required to ensure long-term structural integrity.

Hydrogen production and handling.

TCD yields H_2-rich streams; hydrogen is highly diffusive, with low ignition energy and wide flammability limits, raising the bar on leak detection, ventilation, electrical classification (ATEX/IECEx), and ignition control. Double containment and continuous H_2 detection in machinery spaces; explosion-proof equipment, IP/temperature class checks; purging/inerting for start-up/shutdown.

2.6.4 Offloading Processes

Liquid CO_2 (LCO_2) Offloading

Transferring Liquid CO_2 (LCO_2) from ship to shore requires either a sufficient pressure differential or a dedicated offloading pump, and alignment between ship and terminal pressure regimes is essential for both operational efficiency and the overall sustainability of the CCUS chain. Liquid CO_2 is typically discharged from the vessel's storage tanks to a terminal buffer tank through the ship's manifold using marine loading arms or transfer hoses. Typical design for a marine loading arm used for LNG bunkering has two hoses with one hose dedicated to liquid flow and another for vapour return to maintain pressure balance, as shown in Figure 25. Conventional loading by loading arms of pressurised liquified gas at low temperatures is a well-known technology. The same design can be used to allow LCO_2offloading and vapourised CO_2return.

Figure 25. Marine Loading Arm

Although onboard reliquefaction plants can condense returned vapour, these systems may struggle to fully stabilise tank pressure during high-rate offloading. If vapour return capacity is inadequate, boil-off can accumulate, increasing reliance on re-liquefaction or, in the worst case, forcing venting—both of which negatively affect the net environmental performance of CCS operations. As LCO_2 enters the terminal buffer tank, displaced vapour must also be managed, while the main energy requirement onshore is associated with LCO_2 pumping. The pumping energy required for LCO_2 offloading can represent a significant share of a terminal's overall energy footprint, making it an important factor in lifecycle sustainability. Higher energy use during the transfer stage directly reduces the net CO_2 avoided across the CCUS chain, underscoring the need for efficient pressure management and optimised pumping strategies. As a result, effective pressure control, minimisation of boil-off, and reduction of pumping energy are key levers in improving the environmental performance of LCO_2 transport and disposal.

Port-side capability to receive and process CO_2 captured onboard is still at a very early stage of development. Only a limited number of ports possess any LCO_2 offloading infrastructure, and these facilities are generally designed for food-grade CO_2, resulting in poor interoperability with capture-grade streams. Most downstream utilisation and sequestration projects remain pre-FID (Final Investment Decision), making port authorities cautious about investing in new infrastructure—particularly in already congested terminals where LCO_2 handling requires additional space and enlarged safety buffer zones. Furthermore, standards and operating procedures for OCCS offloading have yet to be established, adding to near-term operational constraints.

This is discussed in more detail in Section 3 Disposal Pathways.

Solid Carbon and minerals offloading

When CO_2 is captured through mineralisation pathways, such as the calcium looping process, the carbon is chemically bound into a stable solid mineral, typically calcium carbonate ($CaCO_3$). In containerised mineralisation systems, solid carbonate is stored in sealed modular containers. The offloading process can be conducted using port cranes. Once offloaded at port, this material can follow different utilisation or regeneration routes depending on the local industrial ecosystem and the vessel's operational model.

In a closed-loop setup, the mineralised product is transported to a shore-based regeneration facility, where it undergoes calcination to release pure CO_2 for permanent sequestration or utilisation. The regenerated sorbent (CaO) is then returned to the vessel for reuse, supporting continuous onboard capture while minimising the consumption of fresh sorbent. Few ports currently provide integrated regeneration capability for calcium looping sorbents.

Alternatively, the mineralised product can be diverted into industrial value chains, most notably the construction sector. Calcium carbonate and related mineralised CO_2 products can be used as additives or fillers in concrete, cement, aggregates, and other building materials, offering both structural benefits and permanent carbon storage. In this scenario, the captured CO_2 remains locked within the mineral matrix indefinitely, eliminating the need for regeneration and contributing directly to long-term climate-mitigation goals. The ability to recycle mineralised CO_2 into commercial materials also reduces disposal requirements and can enhance the sustainability profile of port operations.

Mitigation Measures

Ongoing high-level monitoring of onboard carbon capture and storage (OCCS) developments remains essential as the technology and supporting infrastructure continue to advance. This includes tracking the emergence of new liquid CO_2 (LCO_2) transportation routes, the growth of regional CO_2 handling hubs, and lessons learned from industry case studies and early pilot projects. Establishing such a monitoring framework ensures that shipowners and operators remain informed about evolving logistical pathways, regulatory requirements, and technological progress, enabling more robust planning for future OCCS integration.

Particular attention should be directed toward identifying potential fixed trading routes, also known as green corridors, where long-term agreements can be established between Charterers and receiving terminals. Such arrangements are crucial for managing the full CO_2 value chain, as onshore facilities will ultimately be responsible for safely receiving, processing, and permanently storing or utilizing the captured CO_2 through certified and auditable procedures. Early alignment between vessel operators and shore-based infrastructure providers strengthens commercial certainty, supports investment planning, and helps ensure that OCCS installations can operate reliably within an integrated logistics network.

As outlined in Section 3 on Disposal Pathways, a number of large-scale industrial carbon-management projects, particularly within the cement, refining, and mining sectors, are already advancing to provide substantial CO_2 offloading capacity. These projects can also serve as destination points for CO_2 captured onboard vessels operating in the same geographical region or within connected supply chains. An additional opportunity arises through mineralisation pathways, where captured CO_2 is converted into stable carbonates that can be incorporated directly into construction materials. This approach not only provides permanent sequestration but also enhances material performance. Integrating maritime-captured CO_2 into these industrial ecosystems supports a more cohesive, circular, and resilient carbon-management infrastructure, strengthening both environmental and economic outcomes.

In addition to land-based disposal routes, the potential for offshore or at-sea disposal of captured CO_2, like in the case of Calcarea - Lomarlabs, may also be considered in specific cases, particularly where mineralisation or alkalinity-based pathways are available. However, such options face significant regulatory challenges. Discharges of CO_2-derived streams into the marine environment are subject to strict controls under the London Convention and the London Protocol, which regulate the dumping of wastes and other materials at sea. These frameworks require comprehensive environmental assessments and permitting procedures, and in some cases further regulatory clarification, before such approaches could be implemented at scale. As a result, while at-sea disposal pathways may offer future flexibility, their deployment remains closely linked to evolving regulatory acceptance as elaborated in 4.3.1London Convention & London Protocol.

2.7 Fuel Interactions

2.7.1 Heavy Fuel Oil

The use of Heavy Fuel Oil (HFO) in combination with onboard carbon capture systems introduces distinct challenges due to the fuel's inherently high sulfur content, elevated particulate matter, and presence of metals and ash. These contaminants affect exhaust gas quality and necessitate robust pre-treatment to maintain stable CO_2 capture performance. Without sufficient SO_x removal and fine-particle reduction, the formation of heat-stable salts, solvent degradation, and fouling within absorbers and heat-exchange surfaces can significantly reduce system efficiency. Consequently, SO_x scrubbers become essential, serving as the primary barrier that protects solvents and prevents irreversible chemical reactions within amine-based absorption systems. Additional cooling and conditioning of the exhaust gas are also required to meet absorber inlet specifications, increasing auxiliary power demand and system complexity.

The integration burden is notably lower for vessels already equipped with exhaust gas cleaning systems, as existing scrubber infrastructure can be leveraged to support OCCS operation. This results in a more compact installation, reduced incremental OPEX, and smoother operational workflows. However, when compared with cleaner fuels, HFO operation leads to higher energy penalties, more frequent solvent reclaiming, increased maintenance requirements, and tighter operating margins. Despite these drawbacks, OCCS remains technically viable on HFO-fuelled vessels, provided that pre-treatment, solvent protection, and thermal management are robustly designed and properly maintained throughout vessel operation.

2.7.2 Marine Gas Oil

Compared with HFO, Marine Gas Oil (MGO) produces a much cleaner exhaust stream due to its inherently low sulfur content, which complies with IMO's 0.5% global limit and the 0.1% ECA cap. This substantially reduces SO_x and particulate emissions, eliminating the need for scrubbers and dramatically lowering pre-treatment requirements before OCCS. While MGO still emits CO_2 and NO_x, its distillate nature means the exhaust contains far fewer impurities than HFO, minimizing solvent degradation, heat-stable salt formation, and fouling within the capture system. As a result, OCCS integration on MGO vessels is considerably simpler, with lower energy penalties, reduced maintenance, and more stable long-term capture performance compared with HFO's high-contaminant exhaust.

2.7.3 Methanol

Methanol is one of the most favourable fuels for integration with onboard carbon capture systems due to its inherently clean combustion characteristics. Methanol combustion produces an exhaust stream composed primarily of CO_2 and H_2O, with extremely low levels of sulfur, soot, and metal-bearing particulates. Studies confirm that methanol contains no C–C bond and therefore generates substantially fewer carbonaceous particulates and deposits compared with diesel fuels, resulting in significantly cleaner exhaust and reduced aftertreatment burden. This absence of sulfur virtually eliminates the formation of heat-stable salts and prevents solvent degradation, thereby enhancing absorbent stability and reducing corrosion risks within the capture system (Leng, 2023).

Pre-treatment requirements are correspondingly minimal, generally limited to exhaust cooling, humidity control, and basic particulate removal. Research on methanol combustion shows reduced incomplete-combustion by-products, especially under optimised engine concepts, further supporting the stable operation of downstream systems such as OCCS. Although methanol exhaust typically presents a slightly lower CO_2 concentration than fuel oils, this has only a marginal effect on absorption thermodynamics and does not materially influence OCCS sizing when systems are properly engineered. (Eßer & Peitz, 2025)

Operationally, methanol enables lower energy penalties, simpler exhaust-gas conditioning, and longer solvent lifetime because of the reduced contamination load. Overall, methanol stands out as one of the most technically favourable and integration-ready fuels for OCCS due to its clean emissions profile, minimal pre-treatment needs, and strong compatibility with solvent-based capture technologies.

2.7.4 Liquified Natural Gas

Liquefied Natural Gas (LNG) is highly compatible with onboard carbon capture systems due to its inherently clean combustion characteristics. LNG combustion produces ultra-clean, dry exhaust with no sulfur compounds and almost no particulate matter, eliminating the need for upstream scrubbers, particulate filters, or other flue-gas cleaning systems. Industry assessments confirm that LNG combustion almost eliminates SO_x and PM emissions and significantly reduces NO_x and CO_2 relative to oil-based fuels. This results in a simplified OCCS integration pathway with minimal pre-treatment requirements. (DNV, 2023)

Capture performance remains high, although LNG exhaust contains lower CO_2 concentrations compared with fuel oils due to methane's higher hydrogen-to-carbon ratio. Studies show that LNG can reduce CO_2 emissions by about 23–30% compared with diesel, which inherently lowers the CO_2 partial pressure entering the absorber. As a result, OCCS may require larger contact areas or optimised absorber configurations to maintain equivalent capture efficiency.

OCCS on LNG typically exhibits a 10–15% higher specific energy demand, driven by the lower CO_2 content of the flue gas. However, the absence of contaminants substantially reduces auxiliary loads and operational complexity. Additionally, certain LNG-fuelled systems can recover cold energy from the cryogenic fuel supply chain, which can partially offset refrigeration or compression power and enhance overall system efficiency.

LNG-fuelled vessels are also suitable candidates for pre-combustion carbon capture approaches, given the clean gas properties and compatibility with reforming-based architectures. Overall, LNG offers one of the most streamlined and technically favourable pathways for OCCS integration.

2.7.5 Biofuels

Biofuels such as Hydrotreated Vegetable Oil (HVO) and Fatty Acid Methyl Ester (FAME) are highly compatible with onboard carbon capture systems due to their inherently clean combustion characteristics. Both fuels contain little to no sulfur and have significantly lower impurity levels than conventional marine fuels, meaning their exhaust streams are dominated by CO_2 and H_2O, with only trace NO_x emissions. Technical studies confirm that HVO contains no sulfur or aromatics, producing cleaner exhaust and lower particulate emissions, while FAME burns with reduced soot formation due to its oxygen content. These properties support stable, high-efficiency CO_2 capture performance comparable to methanol and LNG. (Spectra Fuels, 2024)

The energy demand for OCCS operating on biofuels is low to moderate, depending on blend quality and particulate behavior. Fully renewable fuels such as neat HVO typically require minimal pre-treatment, while blended fuels containing small sulfur traces may still necessitate light SO_x cleaning. For these cases, simple seawater scrubbing or fine particle filtration is generally sufficient to maintain solvent integrity and avoid long-term degradation. Industry reviews highlight that HVO and FAME are “drop-in” fuels, compatible with existing ship fuel systems and capable of reducing emissions without major modifications, further simplifying OCCS integration.

Because biofuels combine clean combustion with biogenic carbon neutrality, they enable efficient OCCS operation with low additional energy input. When used as part of a broader decarbonisation strategy, biofuels offer strong potential for reducing net greenhouse gas emissions while maintaining robust capture performance and system reliability.

2.8 OCCS Pilot Projects/Case Studies

2.8.1 Shanghai Qiyao Environmental Technology (SMDERI) - M/V Ever Top

Project Status	Completed
Vessel Type	Container Vessel 14,000 TEU
CCS Technology	Chemical Absorption (Amines)
CCS maker	SMDERI – Qiyao Environmental Technology
Capture rate	Up to 40% or 6.6 t/h
Onboard CO_2 storage	CO_2 Phase: Liquefied CO_2 1 x 100 m^3 Type C tank
CAPEX/OPEX	CAPEX: $3-5 M est. (OCCS only) LCO_2 tank:~ $2,000 per m^3

This project represents the world’s first end-to-end demonstration of onboard CO_2 capture, liquefaction, storage, ship-to-ship (STS) offloading, downstream transport, and industrial utilisation. It was delivered by the Global Centre for Maritime Decarbonisation (GCMD) and SMDERI-Qiyao Environmental Technology (SMDERI-QET), with Evergreen Marine's Ever Top as the pilot platform.

During the first operational phase led by SMDERI, the vessel (Figure 27) captured and liquefied 25.44 t of CO_2, achieving consistently high purity levels exceeding 99.9% at all custody-transfer points (Figure 26). The first STS transfer, performed at Yangshan Deep-Water Port to the CO_2 carrier Dejin 26, marked a global milestone and demonstrated that STS LCO_2 offloading is technically feasible and operationally safe when conducted under LNG/LPG-derived transfer protocols. Approximately two-thirds of the captured CO_2 was delivered downstream, with the balance attributed to process losses including boil-off, flashing, line-conditioning vents and residual tank retention.

A second major milestone occurred in January 2025, when Ever Top conducted the first overseas offloading of onboard-captured CO_2 at the Port of Rotterdam, discharging a 20-ft ISO tank container of LCO_2 using standard port-crane operations. This operation demonstrated that containerised LCO_2 handling can be integrated into European port logistics and validated cross-border compatibility of onboard CCS value-chain operations.

Together, the Yangshan and Rotterdam operations underscore the importance of value-chain integration: ensuring alignment between the intended transfer volume and the receiving vessel or terminal's available tank capacity, fully preconditioning receiving tanks to maintain stable liquid loading conditions, and addressing the operational and certification parameters that directly influence transfer performance.

Following offloading, the CO_2 was delivered to Baorong Environmental for utilisation in low-carbon calcium carbonate ($CaCO_3$) production and post-carbonated slag, confirming compatibility with industrial CO_2-to-materials pathways. Overall, this pilot demonstrates both the technical feasibility of integrating amine-based OCCS into container-vessel operations and the operational refinements required to scale maritime CCS deployment across global liner trades.

Figure 26. Demonstration of the world's first end-to-end carbon value chain

Figure 27. Overview of SMDERI-QET's OCCS system onboard the Ever Top

2.8.2 Wartsila – Solvang

Project Status	Ongoing
Vessel Type	LPG Tanker 21,289 m^3 (Clipper Eris)
CCS Technology	Chemical Absorption
CCS maker	Wartsila
Capture rate	Up to 70-75%
Onboard CO_2 storage	2 x 350 m^3 Type C CO_2 tanks ~ 800 tonnes storage capacity
CAPEX/OPEX	CAPEX: $6-9 M est. (OCCS only) OPEX: 100 $/t captured

The CCS project onboard Solvang's Clipper Eris, as illustrated in Figure 28 and Figure 29, represents a full-scale installation of an onboard carbon capture and storage system on a commercial vessel, marking a major technological milestone in deep-sea shipping decarbonisation. Developed jointly by Solvang, Wärtsilä, MAN Energy Solutions and SINTEF, and installed during a comprehensive retrofit at Seatrium's Admiralty yard, the system uses amine-based chemical absorption to capture CO_2 from the main engine exhaust before liquefying and storing it in large deck-mounted Type-C tanks. Pilot testing launched in early 2025 and aims to validate performance under operational conditions after earlier land-based trials demonstrated capture efficiencies of around 70–75% and exceptionally high CO_2 purity levels, with laboratory testing at Wartsila's Moss R&D centre confirming 99.98% CO_2 purity, suitable for downstream sequestration or utilisation.

The retrofit includes a 7-MW carbon capture unit integrating capture, refrigeration, liquefaction and storage, with total electrical demand estimated at approximately 10% of propulsion power, 3–5% for the capture process and 6–8% for liquefaction, while roughly 35% of total cycle energy demand is met through heat recovery systems that reduce the overall energy penalty. The pilot is designed to run for a full year in commercial operation and will focus on verifying CO_2 purity stability, optimising engine–CCS interactions and tuning process parameters to maximise performance.

Solvang positions OCCS as a pragmatic and near-term pathway to meet tightening IMO emissions requirements without relying solely on alternative fuels. The company highlights that broader adoption depends on two external enablers: first, the development of global CO_2 reception and offtake infrastructure capable of handling ship-borne LCO_2; and second, the establishment of a predictable regulatory environment, including IMO-level incentives and compliance mechanisms that make CCS investments commercially viable. With seven additional CCS-ready vessels under construction, Solvang intends to scale deployment if the Clipper Eris pilot confirms the expected capture rate, purity levels and operational feasibility.

Figure 28. Installation of CCS onboard Clipper Eris in Singapore

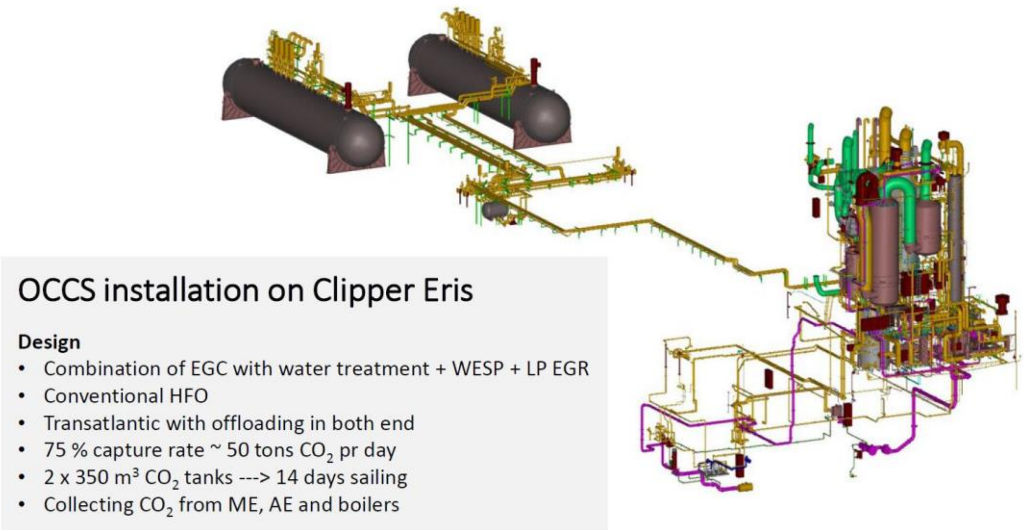


Figure 29. Clipper Eris installation of CCS

2.8.3 Carbon Ridge – Scorpio Tankers

Project Status	On going
Vessel Type	LR2 Tanker STI Spiga (Scorpio)
CCS Technology	Chemical Absorption
CCS maker	Carbon Ridge
Capture rate	Up to 90%

Onboard CO_2 storage	Liquefied CO_2 in Type C tanks
CAPEX/OPEX	CAPEX: tbc OPEX: 120 $/t captured

The CCS project onboard Scorpio Tankers' STI Spiga (Figure 30) involves the installation of Carbon Ridge's compact, modular onboard carbon capture system, developed specifically for maritime applications and retrofitted at Besiktas Shipyard in Türkiye in July 2025. The system is based on a centrifugal absorption architecture, likely using a rotating packed bed configuration, and is designed to significantly reduce space requirements, with Carbon Ridge reporting up to a 75% footprint reduction compared to conventional absorption columns. Its modular layout enables both vertical and horizontal orientations, supporting installation across a wide range of vessel types.

Carbon Ridge indicates that the system is capable of delivering over 90% CO_2 capture efficiency, while also achieving extensive co-pollutant removal, including more than 99% of particulates, SO_x and NO_x. Once captured, the CO_2 stream is compressed, liquefied and stored in onboard Type C tanks for the duration of the voyage, integrated into a broader logistics solution intended to ensure regulatory alignment and compatibility with downstream handling. The technology is fuel-agnostic and is engineered to operate without requiring propulsion modifications, making it suitable for both retrofit installations and newbuilds.

The STI Spiga deployment is part of a wider collaboration between Carbon Ridge and Scorpio Tankers to assess the operational feasibility of compact, centrifugal OCCS systems within commercial tanker operations. With more than $20 million in external funding secured to advance development and deployment, Carbon Ridge positions the system as a cost-effective and scalable onboard solution that can support shipowners in meeting tightening emissions regulations. The pilot's operational period will focus on validating capture performance, onboard integration, system reliability and the practicality of the compact configuration under real operating conditions.

Figure 30. Carbon Ridge Installation on board STI Spiga

2.8.4 Value Maritime – Various Installations onboard (Berge Bulk, Eastern Pacific Shipping, MOL)

Project Status	Ongoing
Vessel Type	Various
CCS Technology	Chemical Absorption

CCS maker	Value Maritime
Capture rate	Up to 40%
Onboard CO_2 storage	The CO_2-saturated amine in storage tanks
CAPEX/OPEX	CAPEX: $2.0m partial system @ 30% capture OPEX: 100 $/t captured

Value Maritime has emerged as one of the most active providers of commercially deployed onboard carbon capture systems, with installations across multiple vessel types including bulk carriers, tankers, container feeders and LNG-powered Ro-Ro vessels (Figure 31). Their core technology, the Filtree System, integrates SO_x scrubbing with amine-based CO_2 capture, enabling both exhaust gas cleaning and carbon removal in a single modular unit. Depending on vessel configuration, the Filtree can achieve up to 15 tonnes of CO_2 captured per day (equivalent to around 30% emissions reduction), with captured CO_2 absorbed into a reusable amine solution and offloaded in port for regeneration or reuse, supporting circular-carbon applications such as greenhouses, beverage production, and other industrial processes.

Since 2021, Value Maritime has expanded its footprint across several major shipping companies. Berge Bulk has installed the system on the Berge Yotei, a 63,000 DWT Ultramax bulk carrier, as part of its decarbonisation roadmap and Maritime Marshall Plan, with sea trials underway following installation in May 2025. Mitsui O.S.K. Lines (MOL) deployed a 15 MW Filtree on the LR1 tanker Nexus Victoria, executed during a Singapore retrofit between December 2024 and March 2025. Similarly, the Samskip / ME2CC consortium is preparing the next-generation compact Filtree for installation onboard the LNG-powered Samskip Kvitbjorn, aiming to reduce footprint by one-third through a modular, height-optimised design integrated with heat recovery and energy-efficiency enhancements. Finally, Eastern Pacific Shipping (EPS) installed the Filtree on its MR chemical tanker Pacific Cobalt, as seen in Figure 31, in early 2023 during a 17-day Rotterdam retrofit, achieving up to 40% CO_2 capture and later becoming the first vessel to receive Lloyd's Register's EACCS class notation for onboard CO_2 capture systems.

Across these deployments, Value Maritime's approach is characterised by standardised, plug-and-play modules, fast installation time, hybrid pollutant removal, and a strong emphasis on circular carbon utilisation rather than onboard liquefaction. Installations already span dry bulk, product tankers, chemical tankers and short-sea logistics vessels, positioning Value Maritime as one of the most widely implemented and operationally proven CCS providers in the maritime sector.

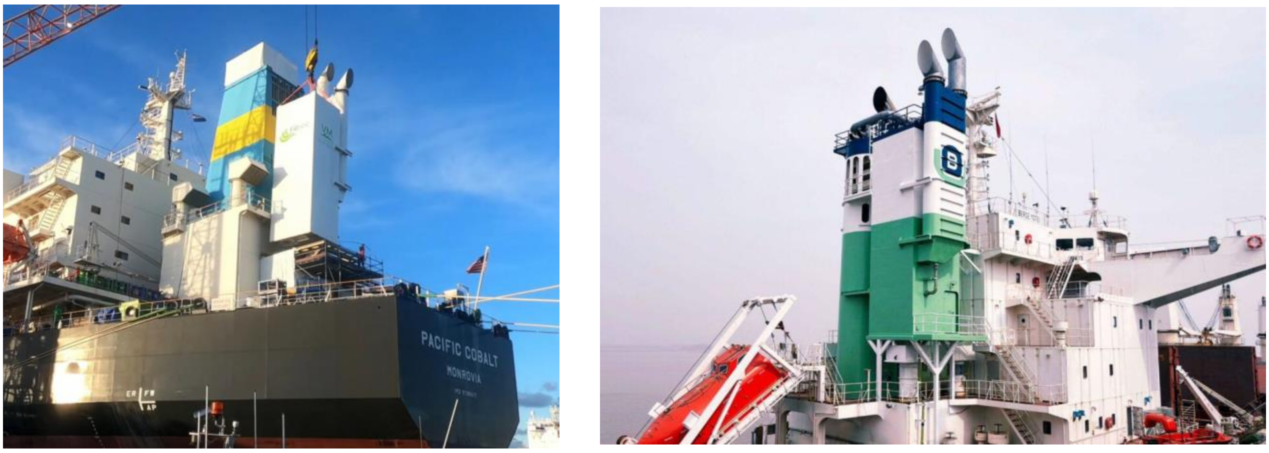


Figure 31. Value Maritime Installations onboard vessels

2.8.5 Seabound – Lomarlabs – Sounion Trader

Project Status	Completed
Vessel Type	Container Ship 3,200 TEU (Sounion Trader)
CCS Technology	Calcium Looping
CCS maker	Seabound
Capture rate	Achieved: 78% CO_2 capture (abt. 1 tonne / day) And >90% SO_x removal during the sea trial
Onboard CO_2 storage	CO_2 stored as solid Calcium Carbonate $CaCO_3$ pebbles
CAPEX/OPEX	CAPEX: $0.5 M est. + container costs OPEX: 100-600 $/t captured

The collaboration between Seabound and Lomarlabs led to the installation and testing of a prototype carbon capture system onboard the 3,200 TEU container vessel Sounion Trader (Figure 32), following a retrofit at the Sefine Shipyard in Turkey in June 2023. The system is based on second-generation calcium looping, whereby CO_2 in the exhaust stream reacts with quicklime to form solid calcium carbonate ($CaCO_3$) pebbles. These pebbles are safe, inert, non-toxic, and easily stored on board for subsequent offloading, where they may be sold in pure form or processed back into quicklime and CO_2 for reuse or sequestration, supporting a circular carbon approach.

Following ABS testing approval and a complementary Lloyd's Register risk assessment, the Seabound team embarked on a two-month sea trial across the Mediterranean Sea, Arabian Sea, and Persian Gulf. Throughout the trial, performance progressively increased, culminating in a 78% CO_2 capture efficiency, equivalent to roughly one tonne of CO_2 captured per day, and more than 90% SO_x removal, confirming the system's ability to address both carbon and sulfur emissions simultaneously. The sea trial validated the practicality of using the Sounion Trader as a floating testbed and demonstrated that calcium looping can function reliably under real-world operational conditions.

The prototype system was fully deck-mounted, modular, and operated using recyclable consumables rather than solvents or high-pressure tanks, simplifying installation and onboard handling. Lomarlabs highlights the technology's potential to scale further, noting the system's projected ability to reach up to 95% CO_2 capture efficiency in future commercial deployments. Collectively, the trial established the technical feasibility of Seabound's approach and laid the groundwork for larger-scale installation across the fleet.

Figure 32 Seabound Installation Onboard

2.8.6 Langh Tech – NaOH Based Onboard Carbon Capture and System

Project Status	Completed
Vessel Type	Feeder
CCS Technology	Chemical absorption using a sodium hydroxide (NaOH) solution.
CCS maker	Langh Tech
Capture rate	Up to 50%
Onboard CO_2 storage:	CO_2 stored as solid sodium carbonate
CAPEX/OPEX:	CAPEX: N/A OPEX: N/A

Langh Tech has developed a post-combustion onboard carbon capture system based on aqueous sodium hydroxide (NaOH) absorption, demonstrated through a pilot installation conducted in 2024 on a vessel operated by its sister company, Langh Ship. In this system, exhaust gases are directed into a capture tower where CO_2 is dissolved into counter-flowing NaOH solution. Through a series of chemical reactions, the CO_2 is converted into solid sodium carbonate (Na_2CO_3), a thermodynamically stable reaction product that can be safely stored onboard without pressurisation or cryogenic cooling requirements.

Pilot testing showed that Langh Tech's system can achieve CO_2 capture rates exceeding 80%, while enabling overall CO_2 emission reductions of 20–30%, depending on vessel layout, available space and integration constraints. These results indicate that the technology can operate reliably and with high efficiency, even within the physical constraints of an existing vessel. The company also emphasises the system's scalability, with flexibility to tailor capture rates by treating only part of the exhaust flow, a feature particularly relevant for smaller ships, feeders or retrofits with limited deck or funnel space.

A notable advantage of the Langh Tech process is the commercial value of the sodium carbonate byproduct, which is widely used in the glass, detergent and chemical sectors. This enables a potential circular-economy model in which the captured CO_2, once mineralised, becomes a marketable commodity rather than a disposal liability. Because the system does not rely on amine solvents, solvent regeneration, or CO_2 liquefaction and compression, it avoids significant energy penalties associated with other CCS approaches and minimises the need for auxiliary equipment. NaOH can also be produced through electrolysis powered by renewable electricity, which further reduces the lifecycle footprint of the system.

Following the successful pilot, Langh Tech plans its first commercial deployments in early 2025 on four bulk carriers, installed by Damen Shipyards Group as part of a wider retrofitting initiative led by Atal Solutions and BAM Shipping.

Figure 33. - Lang Tech onboard carbon capture and storage installation

2.8.7 Hanwha Ocean – BW LNG

Project Status	Completed
Vessel Type	174k LNG carrier BW Cassia
CCS Technology	Chemical absorption using a sodium hydroxide (NaOH) solution.
CCS maker	Hanwha
Capture rate	40% CO_2 capture- abt. 50kg/h
Onboard CO_2 storage	CO_2 stored as solid Calcium Carbonate $CaCO_3$
CAPEX/OPEX	CAPEX: N/A OPEX: N/A

Hanwha Ocean (formerly DSME), is developing an onboard carbon capture system that employs either sodium hydroxide absorption or amine-based capture to remove carbon dioxide directly from marine exhaust streams, with the captured carbon subsequently converted into a mineral form. This approach reflects the company's broader strategy to integrate decarbonisation technologies into high-efficiency LNG carriers, which remain central to its newbuilding programme for BW LNG. According to Hanwha Ocean, the sodium hydroxide-based system chemically reacts with carbon dioxide in exhaust gases to convert it into a stable mineral product, thereby enabling storage onboard without the need for solvent regeneration, cryogenic liquefaction or high-pressure containment. This method forms part of a suite of "versatile eco-friendly technologies" which the company positions as viable near-term measures to reduce greenhouse-gas emissions during vessel operation.

Hanwha Ocean confirms that its onboard carbon capture system is intended to provide shipowners with meaningful emission-reduction capability. The company states that its system can support significant operational reductions in carbon intensity by capturing exhaust-stream CO_2 and converting it into a usable or storable mineral material. This mineralisation pathway avoids the energy demand associated with conventional solvent-based CO_2 handling and fits within Hanwha's broader portfolio of energy-saving technologies installed on its LNG newbuildings, including full reliquefaction systems, air-lubrication systems and shaft-generator technologies. These technologies are already incorporated into the 174,000 m^3 LNG carriers under construction for BW LNG, which form the current platform for the company's decarbonisation integration strategy.

The technology is intended to be fully compatible with modern ME-GI propulsion LNG carriers, such as those being constructed for BW LNG. These vessels incorporate advanced emissions-reduction measures, including highly efficient dual-fuel engines and systems for reducing auxiliary energy demand, therefore providing an appropriate platform for subsequent rollout of onboard CO_2 capture solutions. Hanwha Ocean's stated objective is to integrate carbon-removal capability into such vessels as part of a broader transition towards zero-carbon ship designs, including future ships capable of ammonia-based propulsion and autonomous operation.

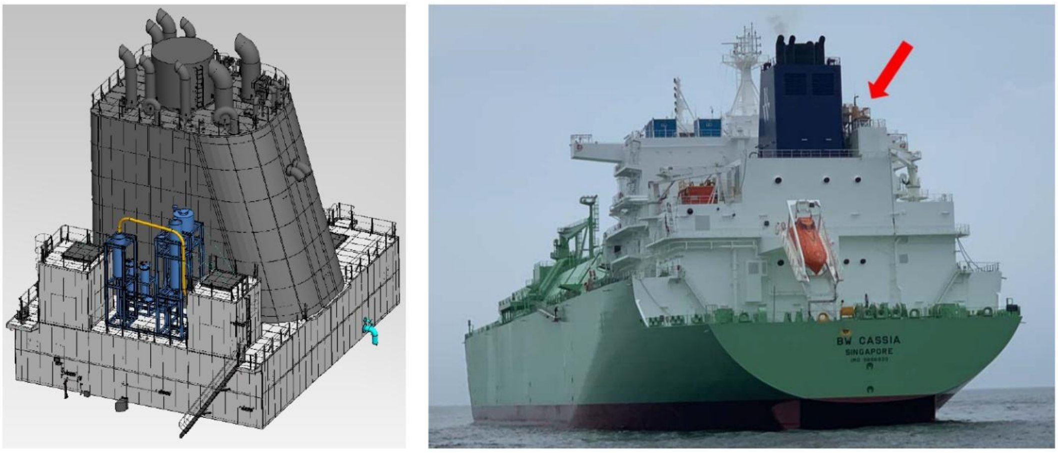


Figure 34. Hanwha Ocean/BW LNG installation

2.8.8 Panasia - Onboard CO_2 Capture System (Container Vessel, 2200 TEU)

Project Status	Completed
Vessel Type	Container Vessel 2200 TEU
CCS Technology	Chemical absorption
CCS maker	Panasia
Capture rate	Up to 90%

Onboard CO_2 storage	Liquefied CO_2 in Type C tanks
CAPEX/OPEX	CAPEX: N/A OPEX: N/A

Panasia has developed an amine-based post-combustion onboard carbon capture system that was installed and tested on a 2,200 TEU HMM container vessel as part of a multi-stakeholder programme with Samsung Heavy Industries and the Korean Register. The system captures carbon dioxide from the vessel's exhaust gases, using waste heat from the main engine to reduce the energy required for solvent regeneration and CO_2 liquefaction, which improves the overall thermal efficiency of the process.

During operational testing, the system achieved capture rates approaching ninety per cent, with liquid CO_2 consistently produced at purity levels above 99.9 percent, verified during the January and May performance assessments. The captured CO_2 was liquefied and stored in Type-C pressure tanks, enabling controlled offloading during port calls. In this pilot, the liquefied CO_2 was supplied as feedstock for green methanol production, demonstrating compatibility with downstream synthetic-fuel pathways and validating the carbon-to-value utilisation concept.

The installation, which proceeded without modification to major onboard machinery, confirmed the technical feasibility of integrating an amine-absorption system into an existing container vessel. Panasia's design includes a full chain of flue-gas pre-treatment, absorption, solvent regeneration, CO_2 drying, purification and liquefaction, supporting stable operation under real maritime duty cycles. The Korean Register's risk assessment and regulatory review further established compliance and operational safety for shipboard deployment.

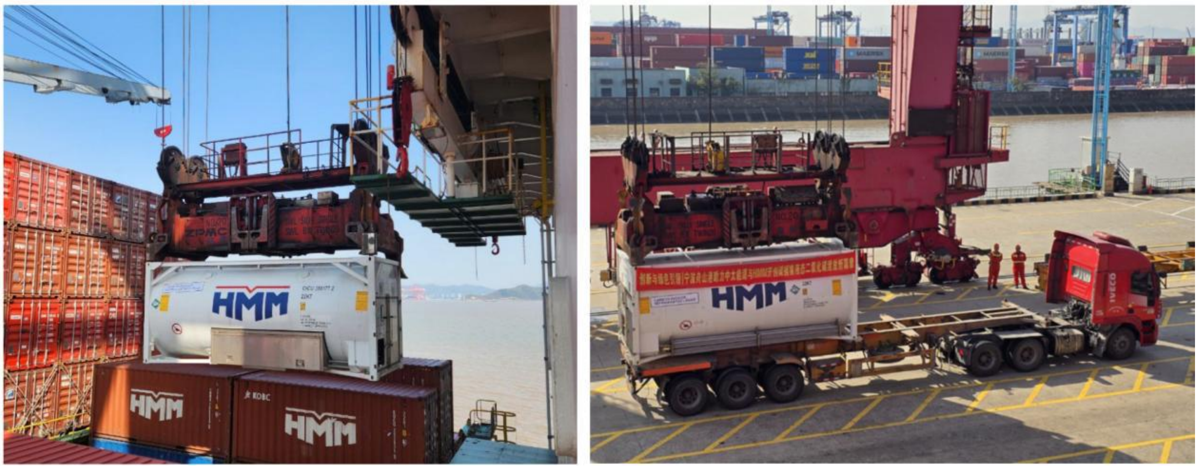


Figure 35. LCO_2 offloading process

Figure 36. Panasia/Samsung Installation

2.8.9 Erma First – Capital Gas

Project Status	In-Progress
Vessel Type	22,000 m^3 LCO_2 carrier
CCS Technology	Chemical Absorption with amines
CCS maker	Erma First
Capture rate	Up to 70%
Onboard CO_2 storage	CO_2 Phase: Liquefied CO_2 in Type C tanks
CAPEX/OPEX	N/A

In June 2024, ERMA FIRST, Capital Gas Ship Management and Babcock LGE signed a Letter of Intent to equip four new 22,000 m^3 liquefied CO_2 carriers with the CARBON FIT CCS system. The vessels as shown in Figure 37, to be delivered in 2026 by Hyundai Mipo Dockyard, will be the largest LCO_2 carriers constructed to date.

The CCS solution combines ERMA FIRST's proprietary amine-based absorption technology used to capture CO_2 from flue gases, with Babcock's ecoCO_2® liquefaction unit, which converts the captured CO_2 into liquid form for storage in pressurised, low-temperature tanks. This enables continuous solvent regeneration and supports an efficient closed-loop capture process.

With Approvals in Principle (AiP) already granted by Lloyd's Register and DNV, the CARBON FIT system is designed to achieve CO_2 capture rates up to 70% range. This capability supports Capital Gas's goal of operating LCO_2 carriers that are close to carbon-neutral, aligning with the strengthened emissions requirements set by the IMO.

Figure 37. Launching of LCO_2 carrier Active (Source: Capital Gas)

2.8.10 Project EverLoNG

Project Status	Completed (2025)
Vessel Type	LNG Tanker 163,285 m^3 (Seapeak Arwa)
CCS Technology	Chemical Absorption with amines
CCS maker	Carbotreat
Capture rate	Abt. 50% (for 17wt% MEA) & abt. 85% (for 30wt% MEA)
Onboard CO_2 storage	CO_2 Phase: Liquefied CO_2 Storage Tank size: 3 x 20 ft containers Capture mass: abt. 250kg CO_2 per day
CAPEX/OPEX	CAPEX: $20m for Newbuilding case consists of the material, installation costs of the equipment and the engineering cost OPEX: 115 EUR/t captured

Project EverLoNG centred on the demonstration of a ship-based carbon capture system developed by Carbotreat and VDL Carbon Capture, installed first on the LNG-fuelled carrier Seapeak Arwa and later on Heerema's heavy-lift vessel SSCV Sleipnir. The system is an amine-based post-combustion capture unit designed to operate under marine conditions, integrating the full chain of capture, liquefaction and onboard storage.

During the Seapeak Arwa campaign, the prototype captured up to approximately 250 kilograms of CO_2 per day, with measured capture efficiencies reaching up to 85 percent depending on the solvent concentration, specifically when using higher-strength amine formulations. The first testing phase accumulated more than 1,000 operating hours and focused on capture stability, solvent behaviour under LNG-exhaust conditions and the impact of vessel motion.

CO_2 captured on board was liquefied and stored in portable containers sized for offshore handling, enabling subsequent offloading for transport to utilisation or permanent storage sites. The process chain included absorption, solvent regeneration, CO_2 drying, purification and cryogenic liquefaction under controlled conditions. The LNG-engine exhaust profile, which contains elevated NO_2 relative to conventional marine fuels, was found to increase solvent degradation rates, representing an operational variable for future system optimisation.

A second demonstration campaign was undertaken onboard SSCV Sleipnir, targeting approximately 500 operating hours to evaluate system behaviour under a different exhaust profile and vessel architecture. This phase included testing the complete CCUS chain under variable loads, along with the effect of ship motion on capture efficiency and solvent performance. Remote monitoring capability from shore was enabled throughout both campaigns to support data acquisition and operational safety.

Figure 38. EverLoNG Onboard Carbon Capture System

2.8.11 Project REMARCCABLE

Project Status	Concept/ Feasibility Study
Vessel Type	MR Tanker Stena Impero
CCS Technology	Chemical Absorption with amines
CCS maker	Alfa Laval
Capture rate	Up to 90%
Onboard CO_2 storage	CO_2 Phase: Liquefied CO_2 Storage Tank size: 380 m3 Endurance: 12 days at a 1295 kg/h CO_2 liquefaction rate
CAPEX/OPEX	CAPEX: \$13.6m (+/-15%) including all costs OPEX: \$830k per year additional fuel consumption, maintenance and periodic amine replacement

Project REMARCCABLE, led by the Global Centre for Maritime Decarbonisation together with Oil and Gas Climate Initiative and Stena Bulk, assessed the feasibility of retrofitting an amine-based onboard carbon capture system onto the MR tanker Stena Impero. The initiative involved Alfa Laval, ABS, Lloyd's Register, Deltamarin and TNO, and focused on the engineering, integration and operational constraints associated with shipboard carbon capture on a medium-range tanker platform.

The feasibility study delivered a full front-end engineering design for an amine absorption system coupled with CO_2 drying, purification and liquefaction equipment. Capital expenditure for the retrofit was estimated at $ 13.6 million (±15%), covering the capture system, liquefaction module and a dedicated onboard liquid-CO_2 storage tank. Detailed costs related to the system design, components and installation are shown in Figure 39. Operating expenditure was assessed at $ 830,000 per year, driven by additional fuel use, support personnel, routine maintenance and periodic amine replacement. The abatement cost, calculated with capital amortised over the remaining vessel lifetime, was projected at $ 769 per tonne of CO_2.

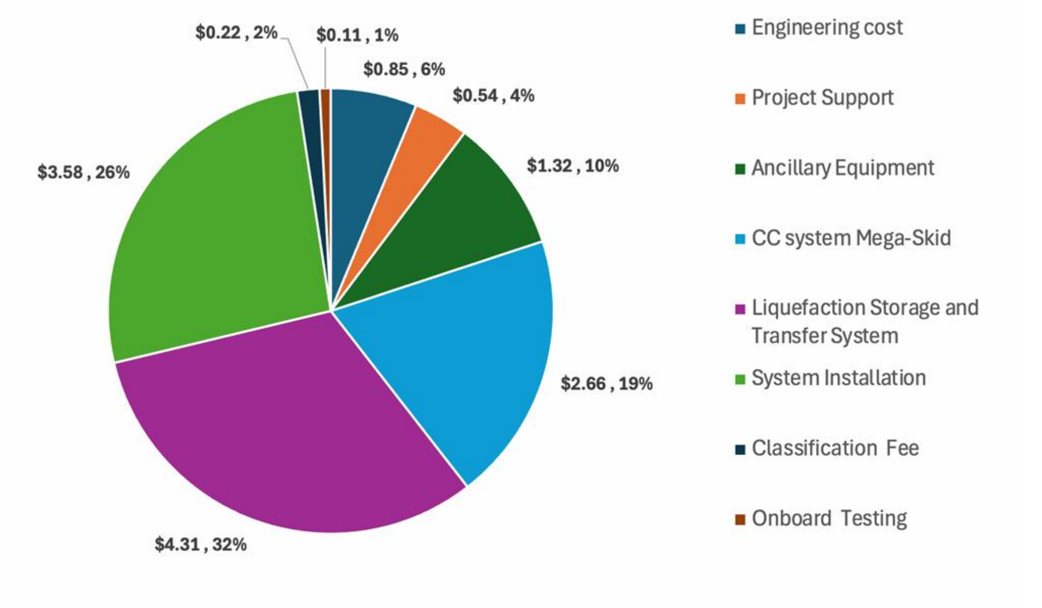


Figure 39. CCS design and installation cost breakdown analysis

Thermal-energy availability was identified as a primary factor influencing system efficiency, as solvent regeneration requires approximately 1,250 kW of thermal energy. With the tanker's existing boiler configuration, supplementary thermal power was required to support the system, creating a fuel-penalty effect of approximately 15%. Engineering review indicated that mechanical reconfiguration of the boiler arrangement could reduce the overall fuel penalty from approximately 15% to about 9%. The system was packaged into a modular skid structure to facilitate onboard integration as illustrated in Figure 40.

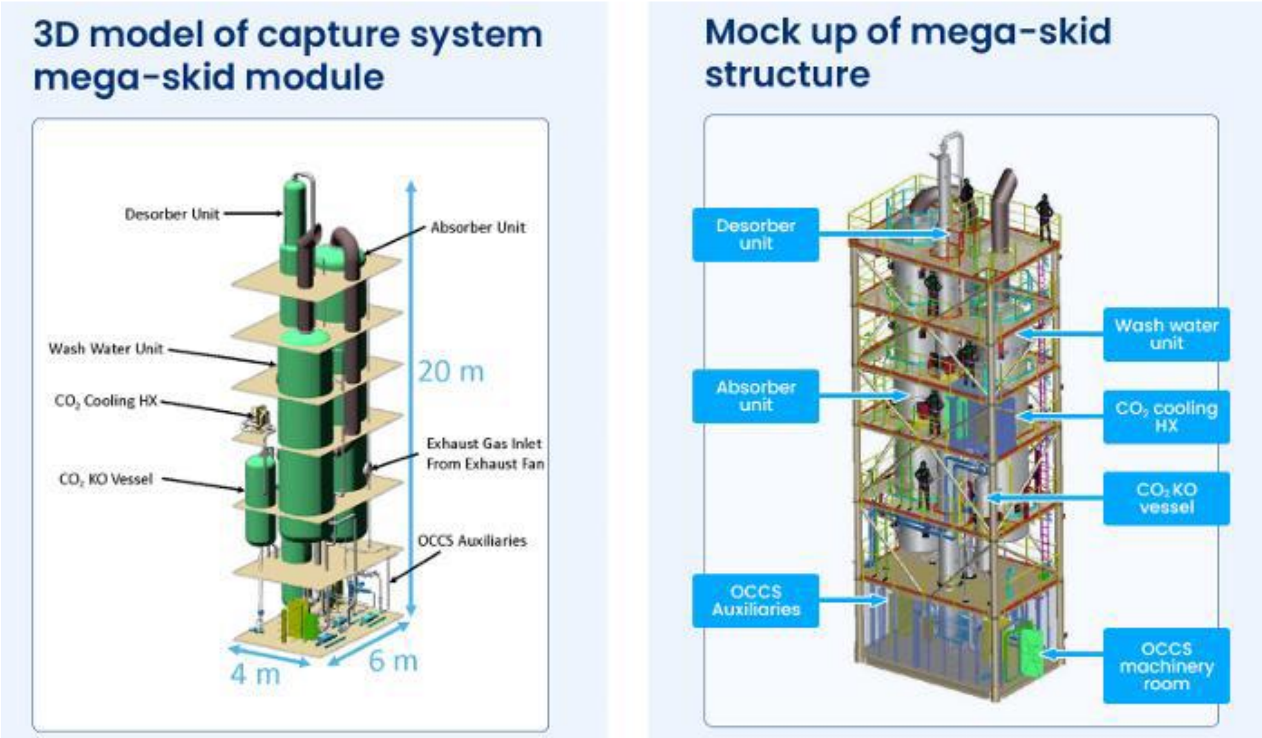


Figure 40. 3D Concept model of the system

Hazard identification and hazard-and-operability studies were completed, leading to Approvals in Principle issued by ABS and Lloyd's Register. Engineering assessments found no technical incompatibilities that would prevent installation of the system on an MR tanker, although scale-up would depend on available deck footprint, thermal margins and operational routing. The study also noted that the vessel could maintain a compliant "C or better" Carbon Intensity Indicator rating for roughly nine additional years if the system were installed.

Several constraints were identified, predominantly related to commercial and logistical factors rather than engineering limitations. These included high initial abatement cost at the retrofit scale and the absence of established port-side infrastructure for receiving liquefied CO_2. The broader project framework incorporated parallel work packages dealing with the development of offloading requirements and regulatory considerations surrounding LCO_2 handling at terminals.

2.8.12 Maersk Mc-Kinney Møller Centre for Zero Carbon Shipping OCCS study

Project Status	Concept/ Feasibility Study concluded in 2022
Vessel Type	Various (Container ship, Bulk Carrier, Tanker)
CCS Technology	Chemical Absorption with amines
CCS maker	Mitsubishi Heavy Industries (MHI)
Capture rate	82% used across case studies
Onboard CO_2 storage	CO_2 Phase: Liquefied CO_2
CAPEX/OPEX	CAPEX: 20%-70% of Newbuild Price OPEX: € 0.5-2m annually, plus additional fuel costs

This feasibility study by the Mærsk Mc-Kinney Møller Centre for Zero Carbon Shipping assesses the potential for OCCS across various ship types such as container, bulk, and tanker segments operating on VLSFO, LNG, and methanol.

It found that that while capture rates can reach 82%, the "effective" emission reduction is lower typically 74-78% because the OCC system itself requires significant additional energy with up to a 45% increase in fuel consumption as shown in Figure 41.

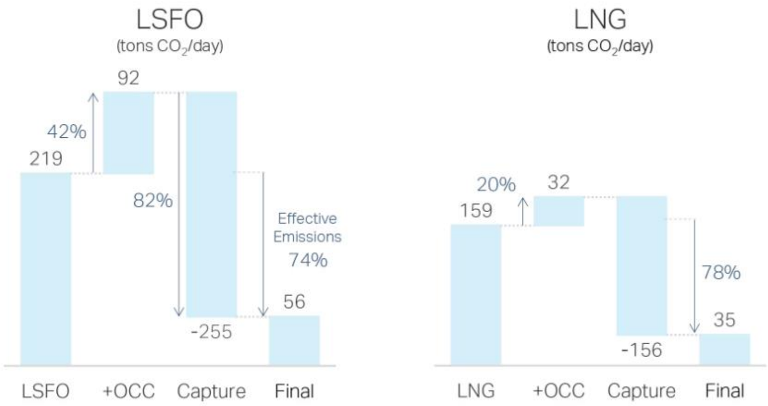


Figure 41. Emission Reduction calculations (Mærsk Mc-Kinney Møller Centre for Zero Carbon Shipping, 2022)

The study estimates that installing an OCCS can cost between 20% and 70% of a vessel's newbuild price, with smaller ships facing disproportionately higher costs due to limited space and lower economies of scale. In terms of operational expenditure, additional fuel consumption accounts for more than 70% of the total OCC-related OPEX, as the system requires significant thermal and electrical energy to operate.

The analysis indicates that tankers, especially large vessels such as VLCCs, are the most favourable platform for OCC integration, largely due to their available deck space and the ability to install LCO_2 storage tanks with minimal impact on cargo capacity. By contrast, small bulk carriers and container vessels experience much higher installation costs and substantial cargo penalties, as their constrained deck and internal volumes limit system placement. Some ship types would also require structural modifications, such as increasing bridge height to maintain visibility over deck-mounted LCO_2 tanks, along with accepting a 3–4% reduction in deadweight capacity. The study concludes that full OCC systems with onboard liquefaction and storage are expected to reach TRL 9 by 2030, positioning them as a viable compliance option within the coming decade.

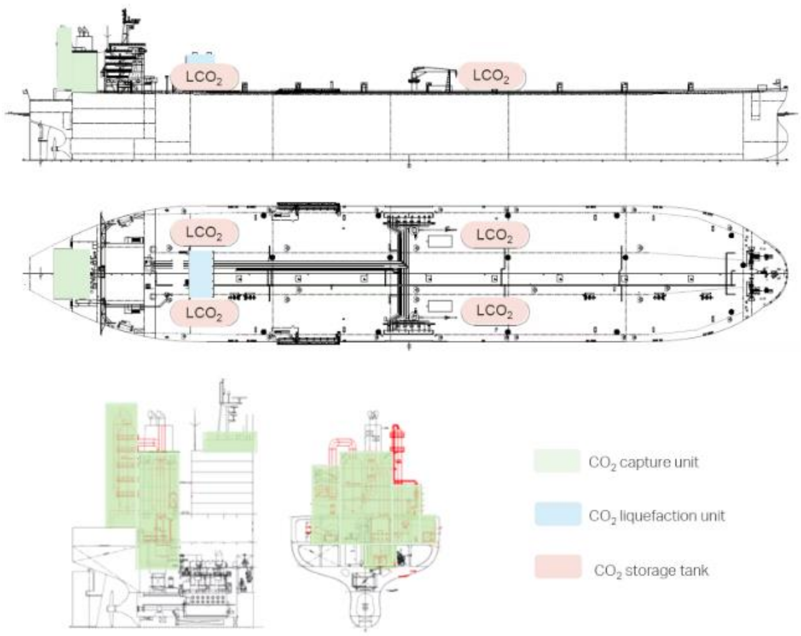


Figure 42. CCS components arrangement concept on board VLCC

2.8.13 META & Aptamus – Ionada Hollow Fiber Membrane Contactor (HFMC) CCS Study

Project Status	Concept/ Feasibility Study
Vessel Type	MR Tanker 46,000 DWT
CCS Technology	Hollow Fiber Membrane Contactors (HFMC) with amines (gas-Liquid)
CCS maker	Ionada
Capture rate	Abt. 60% or 2.3 tonnes per hour (tph)
Onboard CO_2 storage:	Liquefied CO_2 in Type C tanks Storage Tank size: 700 tonnes (~55 tonnes per day)
CAPEX/OPEX:	CAPEX: $6.9m OPEX: 150 $/t captured

The META–Aptamus feasibility study examined the integration of Ionada's hollow fiber membrane contactor (HFMC) carbon-capture technology on a 46,000 DWT medium-range (MR) tanker, supported by funding from the U.S. Maritime Administration (MARAD) (Aptamus, 2025). HFMC technology was selected because of its compact form factor and relatively low energy demand compared with traditional packed-tower amine absorbers, addressing the space and power limitations typical of existing MR tankers.

The system configuration analysed in the study combined gas–liquid HFMC absorption with amine regeneration and downstream CO_2 liquefaction. Integration followed a three-stage sequence: exhaust-gas conditioning, membrane-based amine absorption and solvent regeneration, and liquefied CO_2 storage within Type-C cargo tanks as illustrated in Figure 43. The conceptual design used a 700-tonne onboard LCO_2 storage capacity, corresponding to roughly twelve days of operation (Figure 45).

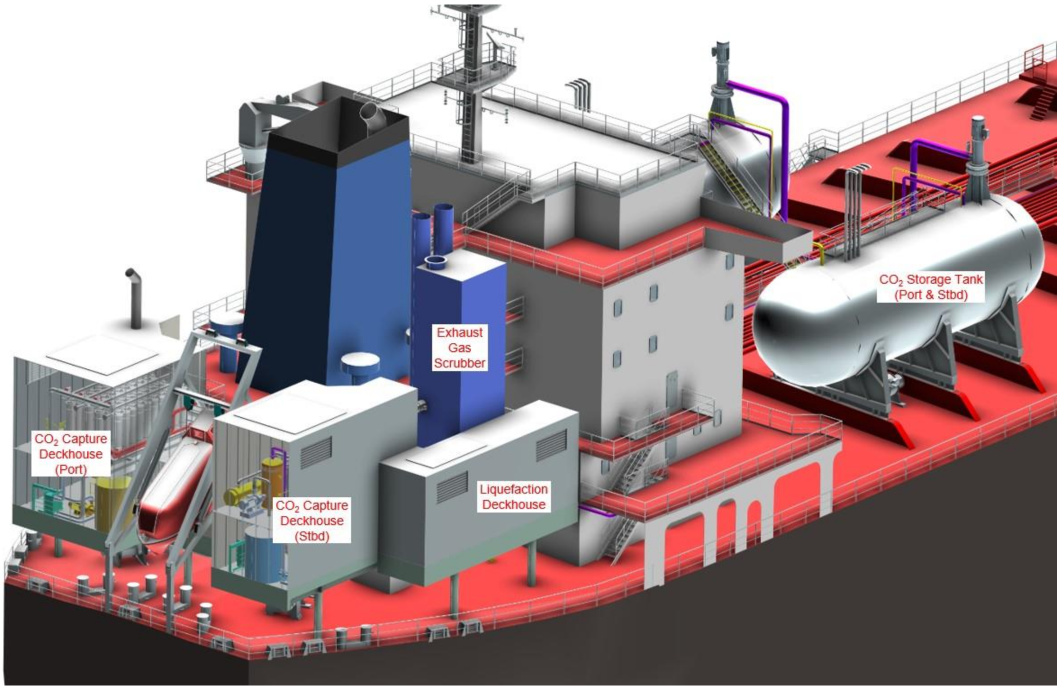


Figure 43. System Configuration (Source: (Aptamus, 2025))

Capture performance was estimated at approximately 60%, or 2.3 tonnes of CO_2 per hour, limited primarily by available waste-heat margin, liquefaction load and onboard storage constraints. The installation and stored CO_2 mass were projected to add more than 1,000 tonnes to the vessel's displacement, directly reducing cargo-carrying capacity at constant draft.

From an energy-integration perspective, the study identified that CCS parasitic load would impose significant demand on the ship's auxiliary power systems, requiring detailed evaluation of onboard electrical generation and heat-recovery arrangements. Liquefaction and low-temperature storage further increased energy requirements. Additionally, impurity management, particularly the control of nitrogen oxides, was highlighted as essential to maintain absorption efficiency and minimise solvent degradation.

Key barriers identified included space constraints, mass impacts, uncertainty around marine CO_2-liquefaction performance and the absence of established offloading infrastructure for ship-captured CO_2.

The expected CAPEX and OPEX associated with installation, operation the CCS system daily were estimated in detail and factored into the overall cost per tonne of CO_2 captured as shown in Figure 44.

CAPEX Estimation

Category	Cost
Front-End Engineering & Design (FEED)	$550,000
Exhaust Gas Scrubber	$1,250,000
Carbon Capture Equipment	$2,500,000
Liquefaction & Purification	$800,000
Type C Storage Tanks	$2,000,000
Deckhouses	$750,000
Shipyard Installation Cost	$1,500,000
Grand Total	$6,850,000

OPEX Estimation

System Capacity	2.3 tph	1 tph
Electrical Demand (kW)	1003.1kW	508.1kW
Heating Load (Steam)	3748 kg/hr	1741 kg/hr
Cost of Electricity (kW) *LSMGO: $700/Ton	$150.46	$76.22
Cost of Regeneration (Steam) *LSMGO: $700/Ton	$127.48	$62.23
Offloading Cost	$34.50	$15.00
Carbon Capture Media refresh	$10.00	$5.00
Maintenance Cost – Hardware	$27.20	$13.60
Maintenance Cost – Personnel	$1.00	$1.00
Total Operating Cost	$336.55	$173.05
Cost per CO_2 Ton	$152.43	$173.05

Figure 44. CAPEX and OPEX estimations

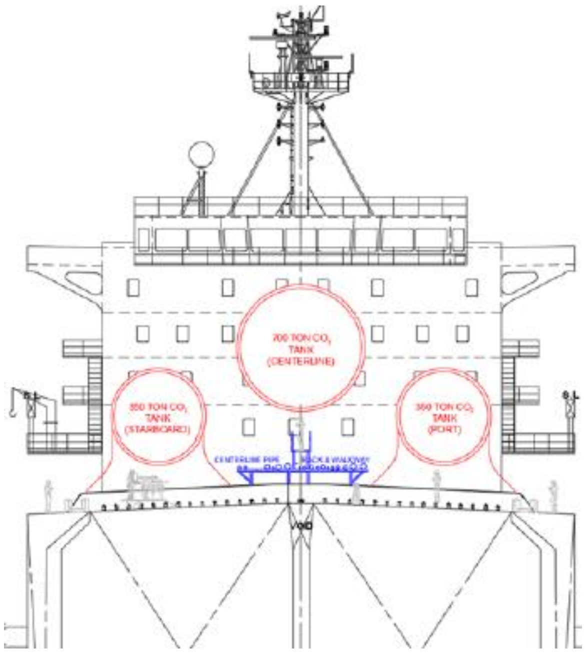


Figure 45. Concept Design for MR Tanker

2.8.14 Project MemCCSea

Project Status	Concept/ Feasibility Study
Vessel Type	Tanker
CCS Technology	Membrane Separation
CCS maker	N/A
Capture rate	Up to 80%
Onboard CO_2 storage	CO_2 Phase: Liquefied CO_2
CAPEX/OPEX	CAPEX: € 6.7m OPEX: frequent reinvestment costs due to membrane replacements

Project MemCCSea, coordinated by CERTH/CPERI (Greece) together with DNV, Fraunhofer, NETL – U.S. Department of Energy, NTNU and EURONAV focused on developing compact post-combustion CO_2 capture systems based on advanced membrane technologies (Figure 46), while addressing maritime integration challenges such as limited space, variable operating conditions, and cost constraints. (MemCCSea, 2022)

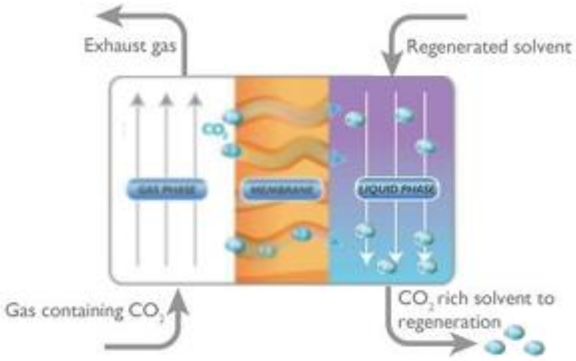


Figure 46. Cross section of a porous hollow fiber wall

MemCCSea investigated two types of membrane technologies:

- Ceramic Gas–Liquid Membrane Contactors
- Polymeric Mixed-Matrix Membrane (MMM) Permeators

The project investigated both laboratory-scale and pilot-scale experimental testing under simulated ship exhaust conditions supported by detailed component-level and system-level modelling (Figure 47). Membrane configurations were optimised for mass transfer, stability, and maritime operating conditions. By the conclusion of the project, both membrane technologies had advanced to Technology Readiness Level (TRL) 5–6.

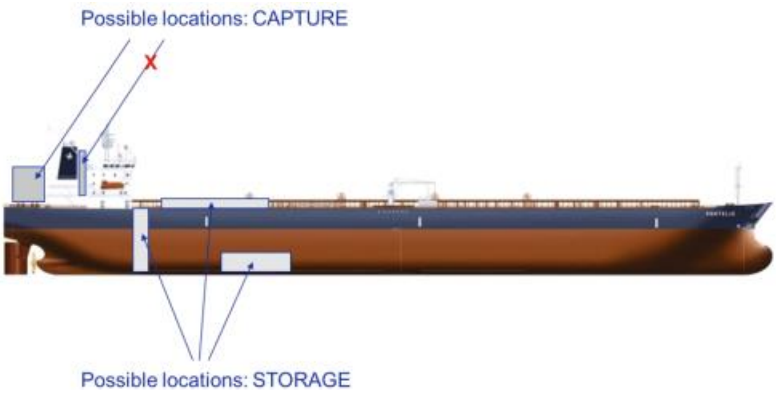


Figure 47. Concept Design for a Tanker (Source: MemCCSea)

Modelling was carried out for both the baseline system and the configuration incorporating membrane-based OCCS, taking into account the additional electricity and heat required to operate the capture unit. Achieving an 80% reduction in emissions resulted in a simulated fuel penalty of 14%. Capital expenditure for the system was estimated at € 6.7 million and ongoing operating costs are driven by regular membrane replacements.

2.8.15 Rotoboost - Wartsila

Project Status	Concept/ Feasibility Study
Vessel Type	LNG Carrier 174k
CCS Technology	Pre-Combustion
CCS maker	Rotoboost

Capture rate	Up to 50%
Onboard CO_2 storage	Stored as solid by-product
CAPEX/OPEX	CAPEX: $7-15m OPEX: N/A

The technical report outlines a joint study by Rotoboost, Wärtsilä, and ABS investigating the integration of a pre-combustion carbon capture system onto a modern 174,000 m^3 LNG carrier (Rotoboost, Wartsila, ABS, 2023). The core technology is Rotoboost's Thermo-Catalytic Decomposition (TCD) system, which uses methane pyrolysis to break down natural gas into hydrogen gas and solid carbon before it reaches the engines. By burning the resulting hydrogen-rich gas blend (typically 89% hydrogen and 11% unreacted methane by volume), the vessel can significantly reduce its direct CO_2 emissions. The study found that decomposing 80% of the natural gas represents the most cost-effective balance for the system.

Placing the TCD system on deck near the BOG compressor reduces gas-piping complexity but adds deck loading, requiring reinforcement. The Decomposer cannot sit directly on the LNG tank due to hot components, so it must be elevated, allowing the space below to be used for solid-carbon storage. The system needs approximately 100 m^2 per 10,000 kg H_2/day, with potential footprint reduction if equipment is arranged vertically; a 200 m^2 layout can fit into about 150 m^2 with 5 m height. The reactors are the tallest component with up to 5 m height including maintenance clearance. Installing the TCD system at the aft simplifies retrofitting, avoids height constraints, and allows exhaust routing through the existing funnel. Alternative system locations are shown in Figure 48.

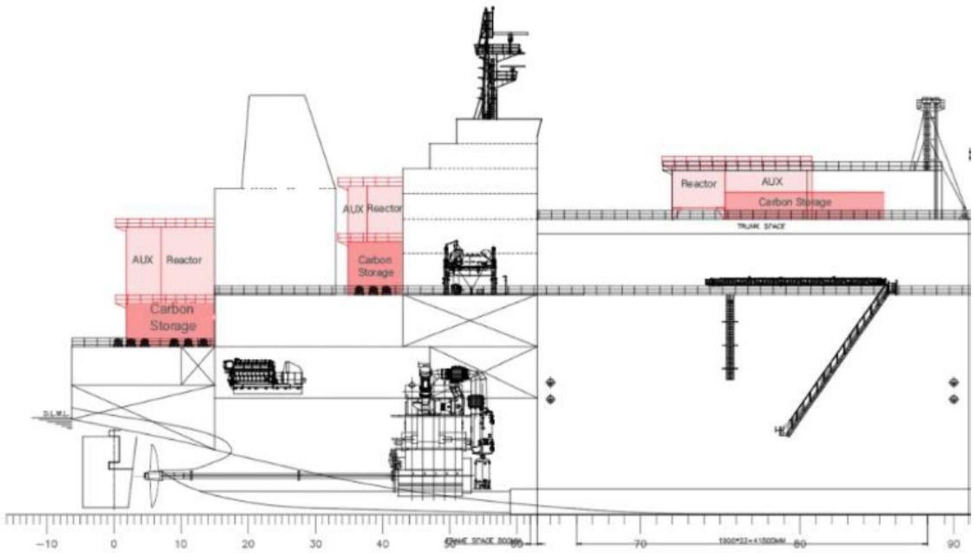


Figure 48. Three alternative system locations (Rotoboost, Wartsila, ABS, 2023)

From a performance perspective, the system achieved a 44% reduction in CO_2 emissions in the baseline study, which can reach 50% if excess heat from the decomposer is recovered for steam or hot water production, as seen in Figure 49. A critical side benefit is the reduction of methane slip, as the high flammability and fast heat release of hydrogen allow the remaining methane to combust more efficiently within the Wärtsilä dual-fuel engines. While the engines require mechanical and automation upgrades for high-hydrogen blends, Wärtsilä's testing confirms the technical feasibility of using these enriched fuel mixtures.

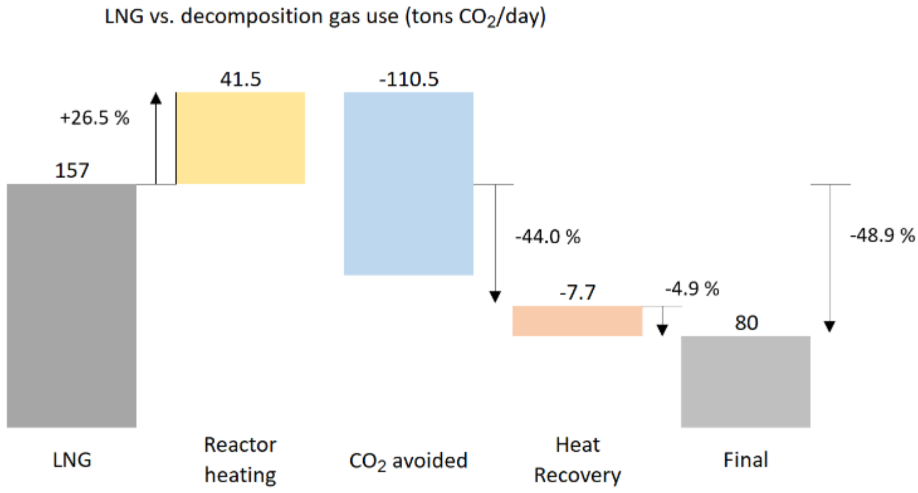


Figure 49. Carbon capture potential of the system

Operationally, the TCD system is designed to minimise impact on cargo capacity by utilising deck space or "back-bag" installations at the aft of the vessel. The modular equipment requires a footprint of approximately 150–200 m^2, with the resulting solid carbon powder stored in dedicated tanks typically located below the system. For a 30-day round-trip voyage, approximately 900 m^3 of storage is required for the carbon byproduct. While the system introduces a "fuel penalty", increasing total natural gas consumption by roughly 70% to produce the hydrogen, it avoids the complex logistics and volume requirements of storing pressurised or liquid CO_2.

2.8.16 Calcarea - Lomarlabs

Project Status	Concept Development Stage
Vessel Type	To be confirmed
CCS Technology	Calcium Looping (Marine Bicarbonate method)
CCS maker	Calcarea
Capture rate	Up to 50%
Onboard CO_2 storage	No onboard storage. CO_2 stored as oceanic bicarbonate discharged/stored at sea.
CAPEX/OPEX	CAPEX: N/A OPEX: 100 \$/t captured (based on costs of 40% limestone, 40% additional fuel, 20% loss cargo)

Founded in 2022, Calcarea has developed a technology based on a deep understanding of ocean carbonate–bicarbonate chemistry. Their process reacts limestone (calcium carbonate) with CO_2 from combustion to generate bicarbonate ions that are stable and environmentally benign in seawater. By using low-cost, widely available limestone and seawater as the reaction medium, the system captures CO_2 and converts it into a durable bicarbonate form as illustrated in Figure 50.

In principle, this approach could enable the discharge of CO_2-enriched seawater into the open ocean, effectively storing carbon as harmless bicarbonate in the upper ocean and accelerating a natural geochemical cycle by many orders of magnitude. However, a critical factor remains the applicable international regulatory framework, primarily the London Convention (1972) and the London Protocol (1996), which govern the dumping of wastes and other matter at sea. The overboard discharge of carbon-carrying seawater remains subject to regulatory uncertainty, and the feasibility of such systems will depend on future clarification and development of international rules governing marine geoengineering and ocean-based storage.

Figure 50. Calcarea working principle (Source: Calcarea)

If regulations allow, Calcarea's technology could be applied in three main areas:

- Onboard carbon capture: capturing CO_2 from marine engines and safely sequestering it in a vessel's wake, offering the maritime sector an additional decarbonisation pathway.
- Sequestration via dedicated vessels: taking CO_2 captured from industrial point sources and storing it offshore without the need for long pipelines or suitable geological formations.
- Atmospheric CO_2 removal: working alongside DAC or BECCS systems to enable large-scale ocean sequestration of captured atmospheric carbon.

Calcarea has completed land-based proof-of-concept testing and is planning a pilot installation on board a vessel in 2026.

2.9 Comparative Assessment of OCCS technologies

This section compares major carbon-capture technology families across key decision criteria, namely; technology maturity, fuel penalty, capital and operational expenditure, environmental and safety performance, and safety based on previously presented pilot projects, feasibility studies, and vendor assessments. The scoring scale of each criterion is based on the following approach:

1 Very Low performance

2 Low performance

3 Moderate performance

4 High performance

5 Very High performance

The assessment aims to provide an initial, high-level comparison of the technologies and is intended for indicative purposes only. While it seeks to quantify and benchmark each option, the results may vary depending on the specific project context and vessel characteristics.

Table 6. CCS Technology rankings

Criteria	Thermo-Catalytic Decomposition	Chemical Absorption	Membrane Separation	Cryogenic Separation	Calcium Looping
Technology Maturity	2	5	3	2	4
Fuel Penalty	2	3	3	2	3
Indicative CAPEX (depends on size/rate)	2	3	3	3	4
Indicative OPEX	2	3	2	3	2
Environmental Performance	4	4	3	5	2
Safety Performance	2	2	3	3	4

Chemical Absorption ranks highest overall. This reflects its high technology maturity, strong environmental performance, and broad commercial readiness. Despite lower safety performance due to solvent handling compared to other methods, it remains the only fully deployable OCCS solution for most ship types today.

Calcium looping emerges as the second top performer with onboard pilots have already validated CO_2 conversion into solid carbonates. It benefits from strong safety performance and relatively low CAPEX, but current environmental and capture efficiency constraints keep it slightly below chemical systems. Its solid-product pathway offers long-term permanence, making it attractive for mineralisation-aligned ports

Membrane Separation sits in the mid-range with its modular/compact system, operational simplicity and balanced economics make it promising for space-constrained vessels. However, lower maturity and moderate capture performance reduce its competitiveness compared with chemical absorption

Cryogenic Separation performs strongly where conditions are favourable with the best environmental performance score, cryogenic systems excel in CO_2 purity, especially on LNG-fuelled or LNG-cargo vessels where cold energy is available. Lower maturity and higher energy demands limit suitability elsewhere.

Although environmentally strong due to high capture potential and solid-carbon output, TCD suffers from low maturity, safety risks associated with high-temperature reactors, H_2 handling and moderate operational complexity. It is promising for future integration however, not yet competitive with more established options.

Table 7. Operational Suitability of Carbon Capture Technologies in Liner and Tramp Shipping

OCCS Technology	Liner Shipping Suitability	Tramp Shipping Suitability	Key Considerations
Chemical Absorption (Amine-based)	High	Medium	• Most mature; Successful pilot-scale marine trials; • Requires heat and LCO_2 handling infrastructure
Membrane Separation	Medium	Low	• Compact/Modular. No chemicals needed • Energy-intensive; limited marine demonstrations. Reliant on availability of shore side CO_2 facilities
Cryogenic Separation	Medium	Low	• High synergy for LNG Carriers, pure CO_2 commercial opportunity • Technically feasible but high power demand; no marine-scale deployment. Reliant on availability of shore side CO_2 facilities
Calcium Looping (Solid $CaCO_3$ Storage)	High	Medium	• No offloading infrastructure needed. • Industrial maturity is higher, but shipboard integration is immature; mass penalty is high
Thermo-Catalytic Decomposition	Medium	Medium	• Lab/pilot maturity only; no marine-ready systems; high energy & hydrogen integration challenges. • Pre-combustion. Avoids LCO_2 logistics. Byproduct (solid carbon) is easier to offload
Calcarea - Marine Bicarbonate Method (Ocean Discharge)	Medium	Low	• Eliminates CO_2 storage and reduces port dependence • Chemistry sound but marine-scale deployment unproven; Discharging bicarbonate into the ocean faces regulatory hurdles

Liner shipping is generally far more suitable for early OCCS adoption than tramp shipping. Liner services operate on fixed schedules, predictable port calls, and repeatable routes, making it easier to arrange CO_2 offloading, infrastructure alignment, and long-term logistics agreements. Tramp vessels, with their irregular trading patterns, face significant challenges securing reliable CO_2 offloading and handling arrangements at ports.

Chemical absorption is the strongest near-term candidate for liner shipping but is poorly suited to tramp operations. As liners operate on fixed schedules between major hubs, they are the ideal candidates for amine systems. Large ports can more easily justify the investment in LCO_2 receiving and processing facilities. However, tramp vessels struggle because amine-based systems require regular offloading, dedicated heat sources, and LCO_2 handling infrastructure, all of which are difficult to guarantee across diverse global ports. If a ship captures CO_2 but cannot offload it because the next port lacks cryogenic infrastructure, the system becomes a deadweight that increases fuel consumption without providing further carbon reduction benefits.

Membrane separation may emerge as a space-saving alternative to amines for liner vessels. The high electricity requirement is often a "deal-breaker" for bulkers and tankers that have limited auxiliary power margins. Additionally, membranes require the same LCO_2 offloading infrastructure as amine systems, which is not widely available for tramp vessels.

Calcium looping emerges as one of the few technologies potentially suited to both segments. its no-offloading requirement and solid-carbon pathway reduce reliance on port infrastructure. Seabound's system is containerised, making it ideal for boxships. These vessels can simply "swap" containers of limestone for fresh quicklime during a standard port call. While the lack of specialised LCO_2 infrastructure is a plus for trampers, the mass penalty is a major drawback. Carrying the heavy lime pebbles reduces the vessel's deadweight making it impractical for long haul voyages.

Thermo-Catalytic Decomposition offers potential cross-segment applicability but remains at early maturity. It could be an effective solution for the tramp sector as it produces solid carbon instead of LCO_2, it does not require specialised cryogenic port infrastructure. The solid byproduct can be offloaded using standard bulk-handling equipment in any port. this technology is specifically optimised for LNG Carriers (LNGCs). Its ability to avoid LCO_2 logistics and produce solid carbon could benefit both liner and tramp trades. Yet, high energy demand, hydrogen-related system complexity, and lack of marine-ready units keep it a mid- to long-term option rather than an immediately deployable one.

Marine bicarbonate (Calcarea method) presents a promising future pathway with symmetrical suitability between both segments. As this innovative system removes the need for CO_2 storage and eliminates port dependence, it could be a strong fit for tramp shipping if regulatory approval and marine-scale demonstrations progress. Liners benefit equally due to minimal operational disruption. However, the method remains unproven at scale and subject to evolving ocean-discharge regulations.

3. Disposal Pathways

Decarbonisation of international shipping requires not only the installation of onboard carbon-capture systems but also the development of robust, scalable pathways for managing the captured CO_2 beyond the vessel. These pathways are typically grouped into three overarching categories: permanent geological storage, industrial and agricultural utilisation, and synthetic fuel production (Power-to-X). Each serves a distinct strategic role within emerging maritime CCUS value chains and is increasingly viewed as part of an interconnected ecosystem.

3.1 Disposal Pathways for Onboard-Captured CO_2

Crucially, the viability of any downstream pathway depends on the ship's ability to offload captured CO_2 into compatible port, terminal, or floating infrastructure. Recent pilots demonstrate that both LCO_2-based and non-LCO_2 (solid/mineralised) CO_2 products can be safely and efficiently transferred using existing maritime operations. The following subsections examine both the offloading mechanisms and the ultimate disposal pathways, assessing their readiness and relevance for maritime deployment.

3.1.1 Offloading Pathways for Liquefied CO_2 (LCO_2)

There are four primary operational concepts for transferring LCO_2 from ships into the downstream value chain (GCMD, 2025)as seen on Figure 51.

- Ship-to-Liquid Bulk Terminal (Direct Terminal Discharge): The vessel discharges LCO_2 directly to a purpose-built onshore terminal equipped with pressurised or refrigerated CO_2 tanks. This model provides the highest throughput and aligns with ports developing CO_2 transport-and-storage systems.

- Ship-to-Floating Storage with Intermediate Receiving Vessel: A floating storage unit (FSU) or receiving barge can act as an intermediary where shore infrastructure is limited or berth occupancy is high. This increases flexibility and discharge operations from terminal availability.

- Ship-to-Liquid Bulk Terminal via an Intermediate LCO_2 Receiving Vessel: In this hybrid model, the ship transfers CO_2 to a smaller LCO_2 carrier which then shuttles it to the terminal. Relevant pilot projects stress the importance of tank pre-conditioning (cool-down, pressure stabilisation) to avoid flashing and boil-off during transfer.

- Ship-to-Terminal via ISO Containers: Captured CO_2 stored in ISO tank containers can be offloaded with standard quay cranes, requiring no liquid-bulk infrastructure. This method is particularly suited for containerships with frequent port calls.

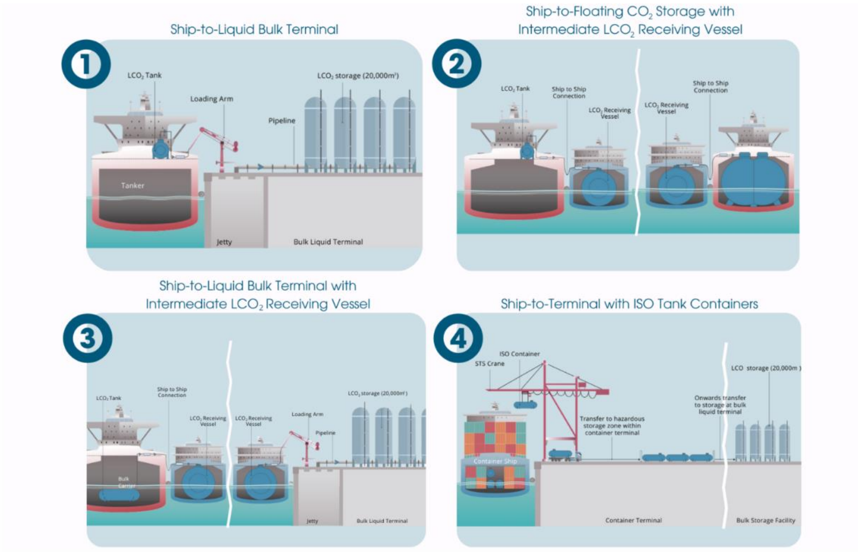


Figure 51. Offloading process of onboard captured CO_2 (Source: GCMD)

3.1.2 Disposal Pathways for Non-LCO_2 CO_2 Outputs

Not all onboard capture technologies produce LCO_2. Emerging systems, particularly solid-sorbent, carbonate-looping, and pyrolysis-based methods, generate solids rather than liquids. These outputs follow entirely different offloading pathways and enable deployment in ports without cryogenic CO_2 infrastructure.

- Carbonate Mineralisation Onboard (Calcium Looping → $CaCO_3$): Calcium-looping systems capture CO_2 by reacting it with CaO to create solid $CaCO_3$, a stable, non-hazardous mineral. Unlike LCO_2 systems, these technologies require no cryogenic storage, eliminate high-pressure CO_2 containment, store captured product in ISO bulk containers and can be offloaded via standard container cranes. This model aligns closely with container-ship logistics and the operational environment of frequent-call liner services. $CaCO_3$ products can feed directly into industrial CO_2-utilisation markets, including cement, concrete curing, mineral fillers and construction materials. Where onshore utilisation markets are unavailable, alternative pathways such as controlled at-sea disposal or long-term storage of $CaCO_3$ may need to be considered, subject to regulatory approval.

- At-Sea Disposal of Calcium Carbonate ($CaCO_3$): As outlined in the previous paragraph, in mineralisation-based capture systems, CO_2 is converted into solid Calcium Carbonate, a stable mineral that naturally occurs in marine sediments and biogenic materials such as shells and coral skeletons. In principle, controlled at-sea disposal of $CaCO_3$ could provide a permanent storage pathway, particularly where particle size, discharge rate, and location are selected to minimise disturbance to marine ecosystems and seabed habitats. However, the intentional disposal of solid materials into the marine environment is regulated under the London Convention and the London Protocol. Implementation of this pathway would likely require permitting, environmental impact assessment, and demonstration that the discharge does not result in unacceptable ecological impacts, including localised sediment accumulation or habitat disruption.

- Solid Carbon from Methane Pyrolysis (Thermocatalytic Decomposition): For LNG-fuelled vessels, pre-combustion pathways such as methane pyrolysis generate hydrogen and solid carbon, thereby avoiding direct CO_2 formation during fuel conversion. In the case of systems such as those developed by Rotoboost, the solid carbon by-product is typically produced as a high-purity carbon powder rather than as fully engineered materials. While this material may serve as a precursor for higher-value carbon products, including graphene or graphene nanoplatelets, additional downstream processing is generally required to convert the raw carbon into such advanced nanostructured forms. From an operational perspective, onboard handling resembles other dry solids, with material stored in sealed bins or containers and offloaded using dry bulk or container-type logistics. The downstream value and utilisation pathways of the carbon product depend on its purity, morphology, and subsequent processing following offloading.

- Discharge of CO_2-Enriched Seawater to the Open Ocean: Certain emerging capture concepts involve dissolving captured CO_2 into seawater, producing a carbon-rich solution primarily in the form of dissolved inorganic carbon (e.g., bicarbonate ions). In principle, this CO_2-enriched seawater could be discharged into the open ocean, enabling carbon storage in dissolved form and accelerating natural oceanic carbon uptake processes. From an environmental perspective, uncontrolled discharge of CO_2-enriched seawater may lead to localized reductions in pH and contribute to ocean acidification if adequate alkalinity buffering is not maintained. Therefore, controlled discharge conditions and chemical balancing are critical to minimise ecological risks.

3.2 Permanent Geological Storage (Sequestration)

Permanent geological sequestration is the most developed, scientifically validated and regulatorily supported method for long-term CO_2 disposal. It provides a high-volume, durable sink for captured carbon and forms the backbone of emerging cross-border CO_2 shipping networks. Operational evidence from large European projects clearly demonstrates both feasibility and scalability.

3.2.1 Strategic Role and Rationale

Permanent geological sequestration ensures that CO_2 removed from industrial or maritime sources is isolated from the atmosphere over geological timescales, eliminating the risk of re-emission. The method is especially critical for hard-to-abate sectors where carbon capture is one of the few viable decarbonisation routes. Because shipping cannot always rely on regional utilisation markets, geological storage provides a guaranteed end-of-life pathway for captured CO_2 and underpins cross-border CO_2 transport frameworks.

Projects such as Northern Lights in Norway and Porthos in the Netherlands represent foundational infrastructure for Europe's emerging sequestration backbone. Northern Lights began injecting CO_2 into a permanent storage reservoir in 2025, establishing operational capability for multi-modal CO_2 receipt by ship. Similarly, Porthos is linking industrial emitters in Rotterdam to depleted gas fields beneath the North Sea, with full operations expected in 2026.

3.2.2 How Geological Sequestration Works

Capture, Conditioning and Transport

Captured CO_2 is compressed and liquefied for transport via pipeline or ship as shown in Figure 52 below. The liquid CO_2 is received at the terminal, transferred to onshore buffer tanks and injected it to subsea reservoirs through a high-pressure, instrumented pipeline.

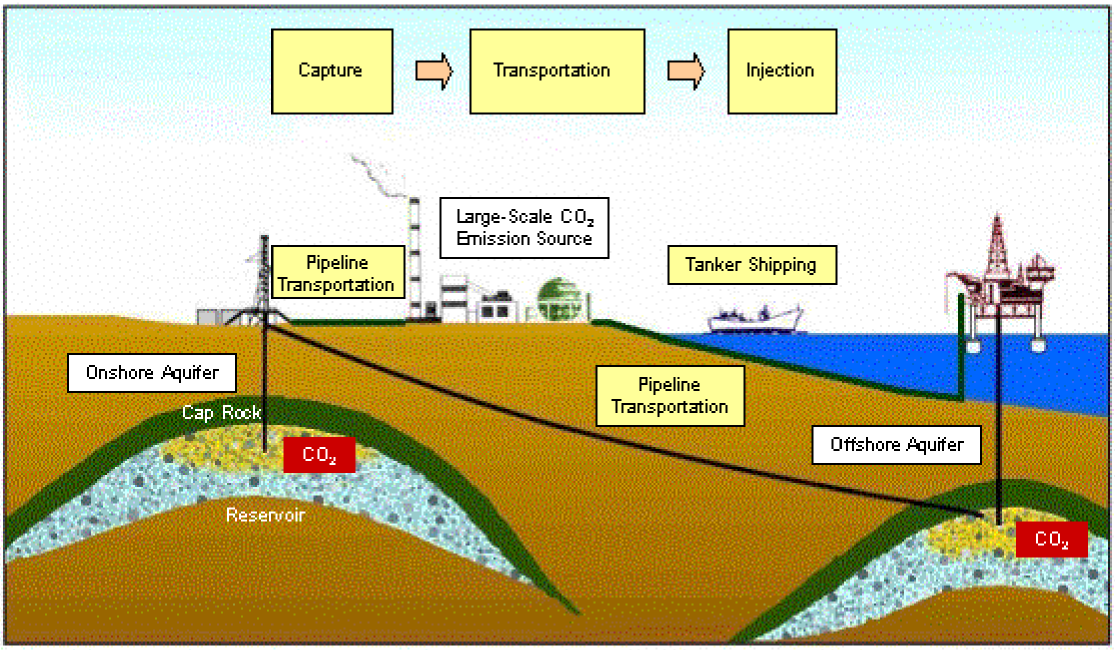


Figure 52. Schematic Diagram of CO_2 geological sequestration technology

Injection and Subsurface Trapping Mechanisms

Once injected below the seabed, CO_2 is stored in porous sedimentary formations overlain by impermeable caprock. At this depth, reservoir pressure and temperature keep CO_2 in a supercritical state. The permanence of storage is achieved through multiple trapping mechanisms:

- Structural trapping: CO_2 is physically contained beneath caprock layers.
- Residual trapping: CO_2 becomes immobilised in pore spaces.
- Solubility trapping: CO_2 dissolves into formation brines over decades.
- Mineralisation: Dissolved CO_2 reacts to form stable carbonates over centuries.

This combination of processes is the scientific basis for the long-term security of geological storage and is central to regulatory approval for injection operations. Northern Lights had already injected *approximately 7,500 tonnes* early in its operational period.

3.2.3 Sequestration in Maritime CCS: Implications and Integration

Role in Future Shipping Networks

Permanent geological storage is a critical component of maritime CCS because utilisation markets will not be able to absorb all captured CO_2, particularly in the early phases of adoption. It provides a reliable backstop pathway, reducing uncertainty for shipowners and supporting investment in CCS retrofits and newbuilds. Large sequestration sites also enable hub-and-spoke systems, where maritime CO_2 carriers collect CO_2 from diverse emitters and deliver it to centralised injection hubs, ensuring that captured volumes can be managed at scale regardless of utilisation demand.

CO_2 Specifications and Quality Requirements

Storage operators such as Northern Lights impose strict CO_2 purity and composition specifications to ensure safety and stability of infrastructure components, including pipelines, injection wells, and storage reservoirs. These specifications govern acceptable levels of water, oxygen, sulphur compounds,

NO_x-derived impurities, and hydrocarbons. Compliance avoids corrosion, hydrate formation, and operational risks.

This has direct relevance for maritime CCS technologies, which must design downstream purification stages (drying, polishing, liquefaction) aligned with these constraints.

Effective shipborne CO_2 delivery depends on the availability of compatible loading jetties and transfer systems at the receiving storage terminal, together with aligned pressure–temperature conditions to ensure safe and stable LCO_2 reception during offloading. A defined offloading cadence is also required to synchronise terminal readiness with onboard storage limits and vessel voyage patterns. In parallel, all transfer operations must comply with international ship–shore interface standards governing CO_2 handling to ensure safe and seamless integration with port-side infrastructure.

3.2.4 Key Barriers and Challenges

Despite strong momentum, several barriers persist:

- High capture costs (>100–150 EUR/t for many emitters), even as storage infrastructure becomes available.
- Need for stable carbon-pricing regimes to support long-term contracts.
- Limited early-stage cross-border legal frameworks for CO_2 transport.
- Sustained public funding required until economies of scale reduce unit costs.
- Long-term monitoring obligations for injection wells and reservoirs.
- Potential bottlenecks in port-side LCO_2 handling and shipping capacity.

These challenges, while significant, are being progressively addressed through EU and national CCUS policies, large-scale investment and maturing commercial models.

3.3 Industrial and Agricultural Utilisation (CO_2-to-Products Applications)

A technically mature and rapidly diversifying set of pathways converting high-purity CO_2 into value-added products across mineralisation, chemical synthesis and biological applications.

3.3.1 Strategic Role and Rationale

CO_2 utilisation plays a dual role in decarbonisation; it creates an economic value from captured CO_2, and provides a flexible, geographically distributed set of sinks while geological sequestration capacity scales up.

The International Energy Agency (IEA) identifies five near-term CO_2 utilisation categories (International Energy Association, 2019); fuels, chemicals, building materials from minerals, building materials from waste, and biological yield enhancement, each of which has the potential to individually scale to at least 10 $MtCO_2$ per year under supportive policy and market conditions. This categorisation is highly relevant for maritime CCS because utilisation pathways typically require high-purity CO_2, which aligns well with solvent-based onboard capture systems; they are often located near major ports, providing accessible regional demand pools (e.g., concrete, aggregates, greenhouse inputs); and they enable circular carbon routes, such as synthetic fuels, that can be re-introduced into the maritime sector

A practical demonstration of this strategic potential is the GCMD–SMDERI-QET case, in which >99.95 vol% CO_2 from an onboard system was accepted by a downstream industrial user for production of low-carbon calcium carbonate and post-carbonated slag, establishing the technical foundations of a maritime-to-industry utilisation chain.

3.3.2 How CO_2 Utilisation Works (Mechanisms & Pathways)

CO_2 utilisation encompasses thermodynamically diverse pathways, each with distinct purity, energy and integration requirements.

3.3.2.1 Mineralisation and Carbonate Products

Mineralisation converts CO_2 into stable carbonate solids such as calcite, providing both permanent storage and access to large-volume product markets. The GCMD Project CAPTURED demonstrated this pathway by converting steel-industry slag into precipitated calcium carbonate (PCC) and post-carbonated slag, confirming compatibility with industrial utilisation routes (calcium-carbonate fillers and construction materials).

Scientific studies report that modified steel slag can achieve CO_2 uptakes of approximately 10 wt%, with CaO recovery rates exceeding 97%, supporting efficient PCC synthesis and high-purity carbonate production suitable for downstream applications. Pressure-swing mineral carbonation is also shown to yield rhombohedral calcite, a morphology widely used in paper, polymer, and cementitious products.

Mineralisation within cement and concrete systems is increasingly recognised as a priority decarbonisation route in Europe, where CO_2 is permanently incorporated into building materials. The U.S. Department of Energy (DOE) emphasises that carbonate formation is a thermodynamically favourable pathway, requiring significantly less process energy than chemical CO_2 conversion to fuels or chemicals, making mineral carbonation one of the most practical early utilisation options for captured CO_2.

3.3.2.2 Industrial and Agricultural Uses

High-purity CO_2 streams are essential for a range of established industrial and agricultural applications, including greenhouse enrichment, beverage carbonation, and specialty process gases. These markets impose stringent compositional specifications, generally requiring CO_2 purities above 99.9%, with tight limits on moisture, oxygen, sulphur compounds, and other contaminants to ensure compatibility with food-grade and industrial-grade standards.

3.3.3 Global Infrastructure Examples Relevant to Shipping

3.3.3.1 Asia-Pacific Industrial Utilisation Chains

Shanghai Qiyao Environmental Technology (SMDERI) - M/V Ever Top project demonstrated the full utilisation chain for ship-captured CO_2 under real operating conditions in China. The pilot included ship-to-ship (STS) offloading of 25.44 t of LCO_2 from Ever Top to Dejin 26, followed by ship-to-truck transfer and overland delivery to Baorong Environmental, where the CO_2 was subsequently converted into precipitated calcium carbonate (PCC) and post-carbonated slag. Throughout all custody-transfer points, CO_2 purity remained above 99.95 vol%, confirming its suitability for industrial utilisation pathways.

3.3.3.2 Mineralisation Hubs (Steel/Cement Clusters)

Steel- and cement-sector industrial clusters are increasingly recognised as strategic hubs for CO_2 mineralisation due to both their high-volume alkaline by-products and proximity to port-based CO_2 flows. Scientific and industrial literature highlights steel-slag carbonation as a major opportunity, with global slag production exceeding 400 Mt per year and providing a large, reactive feedstock for producing high-purity precipitated calcium carbonate (PCC) and carbonated aggregates. In parallel, European cement-sector decarbonisation strategies now explicitly incorporate carbon-mineralised products, including carbonated concrete, aggregates and PCC, into their net-zero pathways, reflecting the sector's recognition that mineralisation can deliver both permanent CO_2 storage and substantial substitution of carbon-intensive cementitious materials.

3.3.4 Utilisation in Maritime CCS: Implications and Integration

3.3.4.1 Quality and Conditioning Requirements

Most CO_2 utilisation pathways impose stringent purity and conditioning requirements, particularly in applications such as hydrogenation reactors, mineralisation processes, greenhouse enrichment, and food-grade industrial gases. These pathways are highly sensitive to trace contaminants including water vapour, oxygen, sulphur species, and nitrogen oxides, all of which can inhibit catalytic processes, degrade product quality, or violate safety standards.

Maritime pilot projects have demonstrated that well-engineered OCCS systems can meet these specifications.

3.3.4.2 Matching Supply Cadence to Industrial Demand

A key challenge in integrating maritime CO_2 with utilisation markets is the mismatch in supply cadence. Industrial offtakers typically operate continuous or semi-continuous processes, whereas onboard CCS produces CO_2 in discrete batch volumes tied to vessel operations. This temporal mismatch requires coordination, storage buffering, or intermediate logistics solutions.

Additionally, transfer-related losses, such as flashing, boil-off, venting during line conditioning, and residual LCO_2 retained in tanks, can reduce the volume of usable CO_2 delivered downstream. GCMD's end-to-end demonstration highlighted that optimisation must focus not solely on capture performance but on the entire value chain, including offloading stability, tank conditioning, and minimisation of custody-transfer losses.

3.3.4.3 Port-Cluster Integration

Ports co located with cement plants, steel slag carbonation facilities, chemical clusters, and controlled environment agriculture represent natural anchors for early utilisation of maritime CO_2. These clusters provide proximity to high purity CO_2 demand centres and enable local circular carbon pathways.

Among these pathways, building materials mineralisation (e.g., PCC, carbonated aggregates, carbonated concrete) offers the largest scalable early stage sink, due to:

- high-volume demand for carbonated construction materials,
- long lasting carbon retention in mineralised products, and
- strong influence from public procurement

3.3.5 Key Barriers and Challenges

3.3.5.1 Limited Aggregate Market Capacity vs Shipping CO_2 Volumes

Although some utilisation markets (e.g. concrete, PCC) are large, they remain insufficient to absorb all global CO_2 from maritime OCCS. The market will remain relatively small in the near term despite strong interest.

3.3.5.2 Purity and Stability Requirements

Utilisation pathways impose strict specifications on CO_2 quality because many downstream processes are highly sensitive to impurities. Contaminants such as sulphur and nitrogen oxides, oxygen, hydrocarbons or excess moisture can interfere with the controlled kinetics of mineralisation or render the

CO_2 unsuitable for food-grade and agricultural applications. These effects can reduce process efficiency, compromise product quality, or create safety concerns. Consequently, onboard CCS systems intended to supply CO_2 for utilisation must incorporate reliable dehydration and purification steps, ensuring that the liquefied CO_2 consistently meets the high purity thresholds required by industrial off-takers. If these conditions are not achieved, the CO_2 may require additional treatment onshore, diminishing the operational and economic benefits of maritime CO_2 utilisation.

CO_2 purity requirements within the CCS value chain will be driven by the balance between purification costs and the capability of downstream infrastructure to tolerate impurities, alongside fundamental safety and integrity constraints. Importantly, shipping is not the primary driver of CCS infrastructure development; instead, it will largely depend on systems designed for large land-based emitters, whose purity specifications are typically stringent and linked to pipeline, compression, and geological storage requirements. As a result, it is unlikely that infrastructure operators will relax purity limits solely for the needs of the maritime sector. While further purification after offloading is technically feasible, it introduces additional cost, complexity, and potential long-term integrity risks for both ships and CO_2 barging assets. Given the current trajectory, any mismatch between shipboard CO_2 purity and CCS network requirements will likely necessitate adjustments on the maritime side. Given the emerging structure of the CCS value chain, OCCS providers will need to take a leading role in meeting required CO_2 purity specifications and design systems with onboard purity monitoring as a standard feature to avoid downstream compliance issues.

3.3.5.3 Logistics and Transfer Losses

Inefficiencies such as pipeline conditioning, venting, boil-off, and residual CO_2 left in tanks can significantly reduce delivered CO_2, requiring innovations in transfer protocols, storage pressures and tank management.

3.4 CO_2-to-Fuels (Power-to-X)

The CO_2-to-fuels (Power-to-X) pathway encompasses a family of thermochemical conversion processes that combine captured CO_2 with renewable hydrogen to produce synthetic fuels suitable for maritime, aviation and industrial use, thereby enabling a circular carbon loop for shipping. In Power-to-X systems, renewable electricity is first used to generate hydrogen via electrolysis; this hydrogen is then reacted with CO_2 either directly or through intermediate syngas production. As illustrated in the Figure 53. below, direct hydrogenation of CO_2 yields fuels and chemicals such as methane, methanol and ethanol, while indirect, where CO_2 is first converted to carbon monoxide via the reverse water–gas shift (RWGS) reaction, enable downstream Fischer–Tropsch synthesis of gasoline, diesel, and aviation fuels.

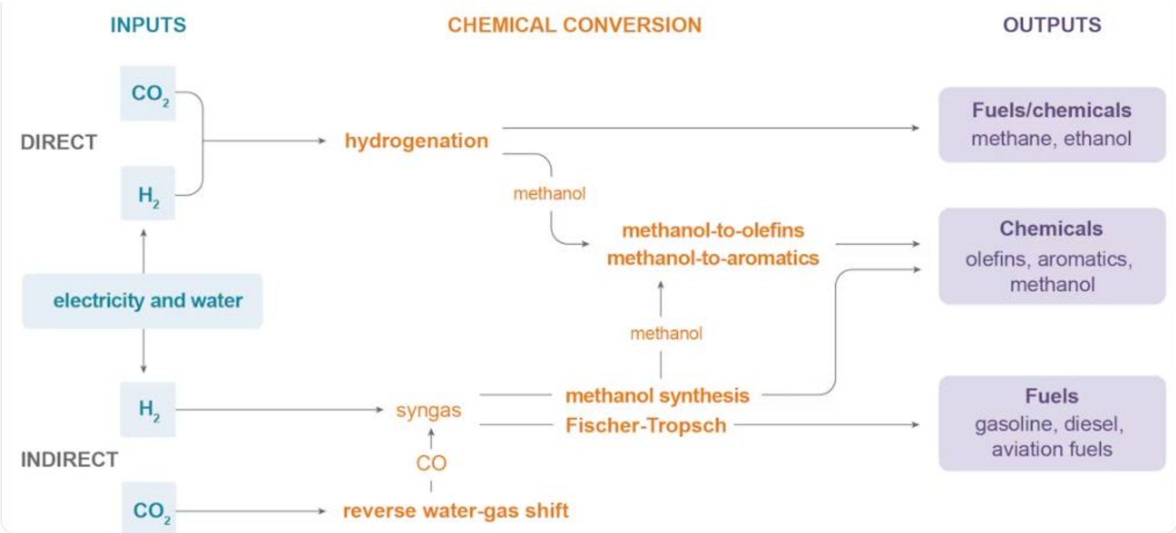


Figure 53. Mature Conversion Route for CO_2 derived fuels and chemical intermediates

3.4.1 Strategic Role and Rationale

Power-to-X (PtX) converts captured CO_2 and renewable H_2 into synthetic fuels and intermediates. Among these, e-methanol is presently the most technologically mature and cost-effective route for near-term scale-up, with compatibility to existing liquid-fuel infrastructure and growing alignment with marine engine platforms, however the production of other fuels like methane and gasoline is also feasible. Fuel production can be classified as one of five near-term CO_2-use categories that can individually scale to $\geq 10\ MtCO_2\ yr^{-1}$, provided low-carbon energy input and robust life-cycle performance; it highlights that quantified LCA and standards are essential to verify climate benefit.

For maritime CCS, PtX provides a closed-loop pathway: onboard-captured CO_2 can be landed at port PtX hubs, synthesised into e-fuels and re-bunkered to vessels. This model leverages the liquid-handling familiarity of ports and engines while reducing dependency on fossil carbon.

3.4.2 How Power-to-X Works (Mechanisms & Pathways)

3.4.2.1 Core thermochemical route: e-methanol (CO_2 hydrogenation)

CO_2-to-fuel conversion relies on the combination of captured CO_2 with renewable hydrogen, and this can occur through either direct hydrogenation or indirect synthesis pathways as outlined in Figure 53. In direct routes, CO_2 reacts with hydrogen over specialised catalysts to form liquid or gaseous fuels such as synthetic methane, methanol, and ethanol, following well-established hydrogenation chemistry. Methanol synthesis, for instance, proceeds via the exothermic reaction of CO_2 and hydrogen at moderate temperatures and pressures, and its industrial maturity is reflected in the high conversion efficiencies reported by commercial licensors which achieves near-total carbon and hydrogen utilisation. Alongside methanol, synthetic methane production via the Sabatier reaction offers a pathway compatible with LNG-fuelled ships, enabling the use of CO_2-derived methane in existing gas-fuelled maritime systems. The IEA recognises both methane and methanol as CO_2-derived fuels that have already been produced in pilot plants processing hundreds to thousands of tonnes of CO_2 per year, pointing to early but established industrial readiness.

3.4.2.2 Alternative/adjacent pathways (Indirect pathways)

Indirect Power-to-X routes expand the accessible product range by first converting CO_2 into carbon monoxide through the reverse water–gas shift (RWGS) reaction. The resulting syngas mixture, comprising CO and H_2, can then be fed into Fischer–Tropsch synthesis, producing hydrocarbon fuels including gasoline-range liquids, diesel, and synthetic aviation fuels. These pathways mirror long-standing petrochemical processes but utilise CO_2 as the carbon source rather than fossil feedstocks. Methanol also serves as a key intermediate linking multiple branches of the Power-to-X network: via methanol-to-olefins (MTO) or methanol-to-aromatics (MTA), the molecule can be upgraded into a wide range of hydrocarbon products suitable for chemicals manufacturing or onward conversion to transport fuels.

3.4.3 Global Infrastructure Examples Relevant to Shipping

Several projects now demonstrate segments of this Power-to-X value chain at operational or pilot scale. The production of CO_2-derived methanol, in particular, is supported by commercial licensing, catalyst supply chains, and early reference plants. Johnson Matthey's eMERALD process, deployed in projects such as Haru Oni in Chile, has enabled the synthesis of renewable methanol from captured CO_2 and green hydrogen, providing a practical example of industrially integrated CO_2 conversion technology. Meanwhile, firms across Europe and Asia have developed pilot plants that produce both methanol and methane from CO_2, often at scales ranging from hundreds to thousands of tonnes per year. These pilots validate the operability of hydrogenation systems under real industrial conditions and confirm the IEA's conclusion that CO_2-derived fuels are among the most advanced utilisation pathways in terms of near-term deployment potential.

Beyond methanol and methane, early demonstrations of synthetic aviation fuel produced from CO_2 via Fischer–Tropsch synthesis are emerging, though these projects remain at the demonstration stage and have yet to reach the maturity of methanol-based technologies. While synthetic gasoline and diesel from CO_2 continue to progress through pilot-scale engineering, they share the same fundamental RWGS-plus-hydrocarbon-synthesis architecture validated in the aviation-fuel pathway. These developments indicate that maritime-relevant PtX fuels, particularly methanol and methane, are already transitioning from laboratory innovation to pre-commercial implementation, with direct relevance for port clusters seeking to integrate captured CO_2 with local green-fuel production.

3.4.4 Implications and Integration with Maritime CCS

The integration of Power-to-X pathways with maritime CCS depends fundamentally on the ability to deliver CO_2 at the purity, stability, and consistency required by catalytic synthesis processes. Hydrogenation and Fischer–Tropsch catalysts are vulnerable to trace contaminants such as sulphur oxides, nitrogen oxides, hydrocarbons, oxygen and moisture, making gas polishing and dehydration essential pre-treatment steps. GCMD's Project CAPTURED demonstrated that shipboard capture systems can supply CO_2 at >99.95 vol% purity, validating its suitability as a feedstock for downstream fuel synthesis where impurity tolerance is minimal. In a Power-to-X configuration located at or near port infrastructure, this high-purity CO_2 stream can be fed directly into methanol synthesis loops or RWGS units, enabling the creation of a circular carbon cycle in which CO_2 captured from ship exhaust is converted into synthetic marine fuels and potentially re-supplied to the fleet.

For ports, this implies a need for co-located electrolysis capacity, CO_2 reception and buffer storage, fuel-synthesis trains (e.g., methanol reactors, methanation reactors or Fischer–Tropsch modules) and the corresponding bunkering systems for synthetic methanol, methane or other e-fuels. The IEA emphasises that the success of CO_2-based fuel synthesis hinges on the availability of low-carbon electricity, coordinated hydrogen and CO_2 handling infrastructure and an integrated conversion system that enables high utilisation of renewable power. For maritime CCS, this alignment creates a natural interface between onboard CO_2 capture and local PtX hubs, turning ports into multi-modal energy and carbon-processing nodes.

3.4.5 Key Barriers and Challenges

Despite the technical promise of Power-to-X fuels, several factors currently constrain their broader deployment. The most significant barrier is the energy and cost intensity of the hydrogen supply chain, as electrolysis remains the dominant cost driver in e-fuel production. Even though methanol is considered the most technologically mature and cost-effective PtX fuel option, its competitiveness depends heavily on reductions in renewable electricity cost, improvements in electrolyser efficiency and economies of scale in fuel-synthesis plants. Another critical challenge is verifying the life-cycle climate benefit of CO_2-derived fuels. Meaningful emissions reductions require low-carbon electricity, verifiable CO_2 origins and transparent accounting to ensure that the overall process results in net decarbonisation rather than energy-intensive recycling.

In addition, PtX catalysts impose stringent impurity restrictions on the CO_2 feedstock, necessitating high-grade dehydration and gas-cleaning steps that add cost and operational complexity. While maritime pilots show that high-purity CO_2 can be reliably generated and delivered, maintaining this quality across varied ship operations remains a non-trivial engineering consideration. Storage, bunkering and port integration also require investment in new infrastructure and regulatory alignment, particularly for fuels such as synthetic diesel or aviation fuels that involve more complex production chains.

Finally, while methanol and methane pathways have moved into consistent pilot and early commercial use, gasoline-range hydrocarbons and e-SAF remain at demonstration scale, and their future deployment depends on continued advances in Fischer–Tropsch technology, green-hydrogen availability and supportive market conditions.

3.5 Port Infrastructure

3.5.1 Overview of Global CCS Deployment

Global deployment of Carbon Capture and Storage (CCS) is accelerating, but progress remains uneven across regions. As of 2025–2026, 38 operational CO_2 storage projects are active worldwide, with a further pipeline of higher-capacity hubs now moving through FEED (Front End Engineering Design) and FID (Final Investment Decision) stages. Current global geological storage capacity of ~71 Mtpa in 2025 is expected to expand sharply, with projections indicating a scale-up to ~450 Mtpa by 2030, driven primarily by policy support in the United States, Europe, and selected Asia–Pacific jurisdictions. In the United States, federal incentives, most notably the Section 45Q tax credit which provides financial compensation per tonne of CO_2 captured and permanently stored, continue to support CCS deployment. However, recent revisions to grant funding programs and evolving federal priorities have introduced increased policy uncertainty, which may influence the timing and scale of future project development. This rapid increase aligns with growing industrial decarbonisation demand, expanding CCS business models, and the emergence of dedicated CO_2 transport and storage operators.

Deployment is heavily concentrated in the United States as per Figure 54, which accounts for roughly half of all global operational projects, supported by a long-standing CO_2 pipeline network, favourable geology, and strong fiscal incentives such as the reformed 45Q credit. Europe represents approximately 6–8% of today's operational capacity but is positioned for one of the fastest growth trajectories globally. More than 50 announced European CO_2 storage projects, supported by the EU Industrial Carbon Management Strategy, CEF-Energy grants, and Innovation Fund mechanisms, are expected to lift European injectivity significantly by 2030.

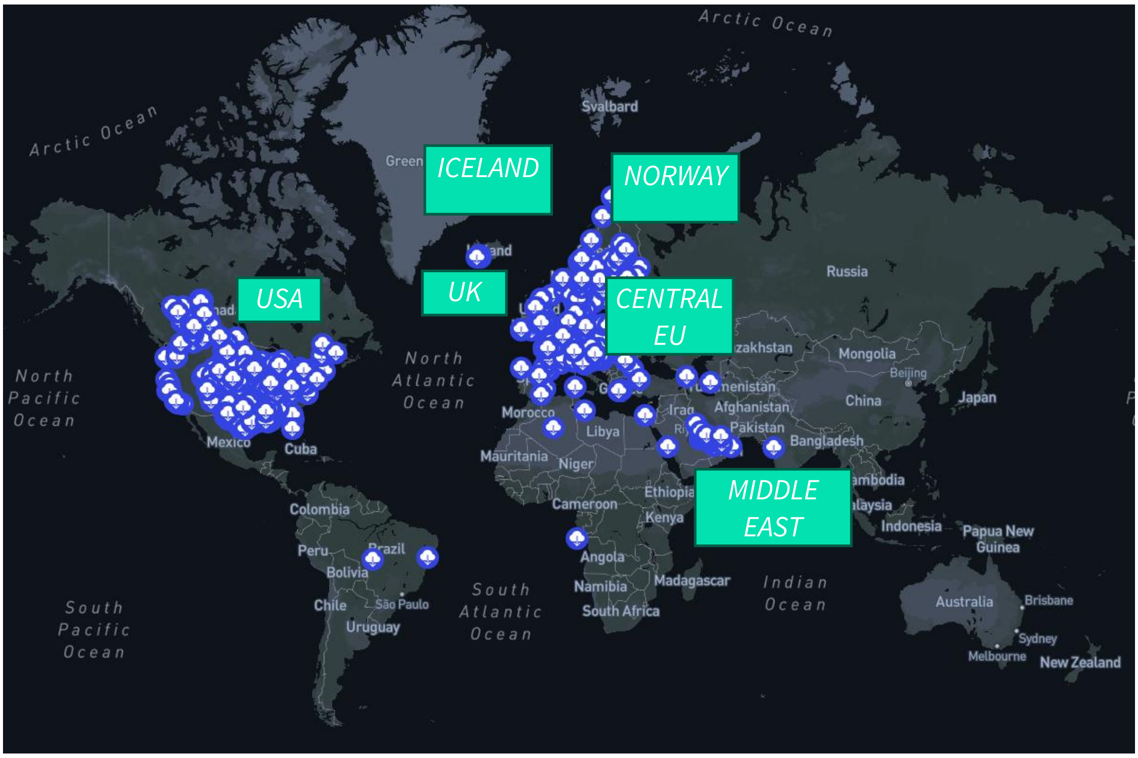


Figure 54. Overview of CCS Projects globally

Geographically, CCS developments cluster around mature industrial basins:

- North America, where large-scale pipeline systems and onshore saline reservoirs form the backbone of planned capacity growth.
- North Sea Europe, where offshore storage provides the most credible medium-term scalability.
- The Middle East, leveraging oil and gas competencies and subsurface capacity.
- Asia–Pacific, progressing through multi-country partnerships and early vessel-based CO_2 transport solutions.

This global landscape creates strong regional asymmetry: storage-rich regions (Norway, Denmark, the Netherlands, UK, US Gulf Coast, Middle East) are increasingly positioning themselves as cross-border service providers, while CO_2-intensive economies without domestic storage (e.g., Belgium, Singapore, Japan, South Korea) develop policy frameworks for import-to-storage value chains.

3.5.2 CCS Facilities in Europe

Europe is transitioning from ambition to execution, with a rapidly expanding project portfolio across 14 countries as we can see in Figure 55. As of 2025–2026, 53 announced CO_2 storage projects span the North Sea basins, Baltic region, Mediterranean states, and an emerging cluster of Eastern European initiatives. These projects represent a structural shift toward infrastructure-led decarbonisation, supported by EU climate policy, national industrial transition plans, and substantial public co-funding.

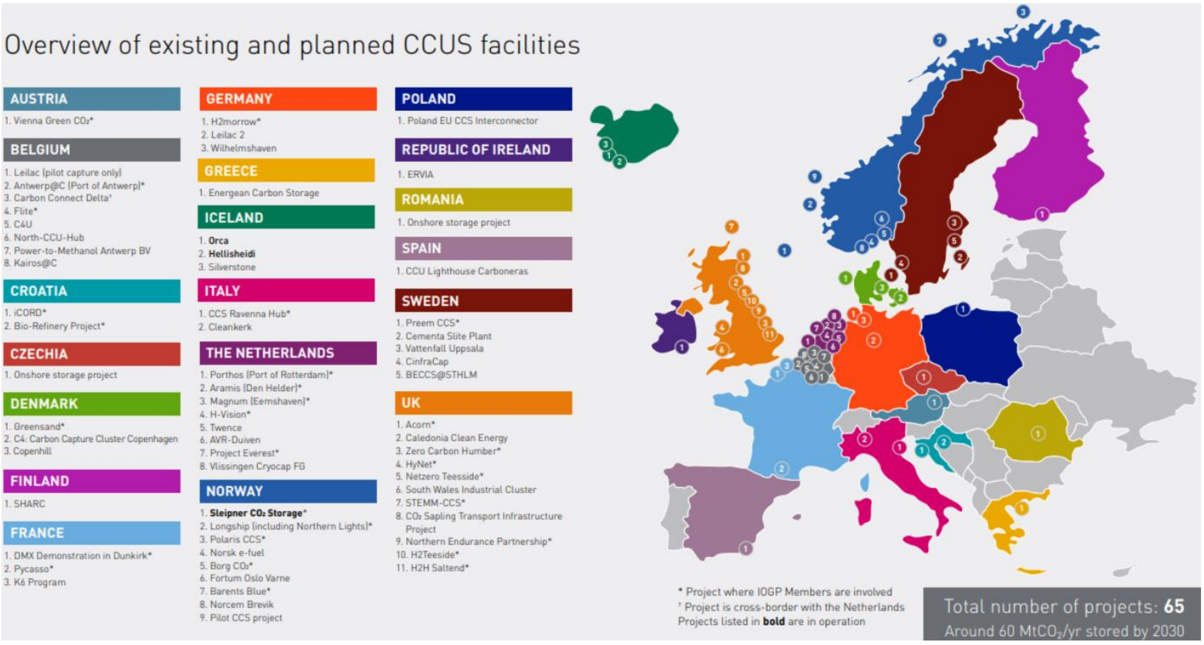


Figure 55. Overview of planned CO_2 storage projects in Europe

The North Sea cluster remains the core of Europe's CCS ecosystem. Norway, the United Kingdom, the Netherlands, and Denmark lead development with large-scale offshore storage projects, integrated CO_2 transport networks, and cross-border arrangements that enable third party access. Flagship examples include:

- Northern Lights (NO), the first fully open-access, cross-border CO_2 transport and storage service receiving CO_2 by ship.
- Porthos (NL), connecting Rotterdam's industrial cluster to depleted offshore gas fields through a shared pipeline and compressor infrastructure.
- Aramis (NL), a large transport backbone enabling multi-user access from Western European industrial centres.
- Acorn (UK) and HyNet (UK), targeting both industrial clusters and hydrogen production.
- Greensand (DK), building offshore storage capacity in the Danish North Sea.

Beyond the North Sea, new regions are entering the CCS landscape. Countries such as Italy, Greece, Croatia, Slovakia, Bulgaria, and Iceland are at early feasibility or pre-FEED stages, supported by EU funding instruments and national decarbonisation strategies. Southern Europe has begun to explore Mediterranean offshore structures as potential storage sites, while Central and Eastern Europe investigate onshore saline aquifers and depleted gas fields.

Europe's CCS maturity is therefore characterised by large-scale offshore hubs serving multiple emitters across borders, anchored in the North Sea and new entrant countries focusing on domestic onshore storage potential or future integration into pan-European CO_2 networks.

This combination of mature and emerging initiatives positions Europe to significantly expand its CO_2 storage capacity by 2030, contingent on final investment decisions, permitting progress, and the development of interoperable cross border CO_2 transport corridors. Current EU policy under the Net Zero Industry Act aims for at least 50 million tonnes of annual CO_2 injection capacity by 2030. Achieving this target will require scaling up operational storage projects, advancing geological storage approvals, and integrating infrastructure to allow CO_2 captured in one region to be transported and stored efficiently across borders.

3.5.3 Summary of Ports with CO_2 Reception Capabilities, Technical Requirements and Disposal Pathways

While maritime OCCS technologies continue to mature, the ability to offload captured CO_2 remains heavily dependent on a very small number of ports with either operational or planned reception infrastructure. These early-stage hubs, primarily located in Northern Europe, represent the first practical interface points between shipboard capture systems and downstream CO_2 transport, utilisation, or permanent storage infrastructure. Their technical specifications (purity requirements, pressure–temperature envelopes, flow capacities) and disposal options (geological sequestration, industrial utilisation, Power-to-X pathways) illustrate both the current enabling conditions and the constraints that ship operators will encounter when planning OCCS deployment.

Table 8. Ports with Existing or Announced CO_2 Reception Facilities & Technical Requirements

Port / Hub	Status	CO_2 Purity Requirements	Pressure Requirements	Temperature Requirements	Flow/Capacity
Rotterdam (NL)	Under development (Porthos)	≥95–99.9% CO_2; strict limits on SO_x/NO_x, H_2O, hydrocarbons	6–22 bar typical for LCO_2 transfer	–30°C to –50°C (cryogenic transfer envelope)	~1–5 Mtpa planned terminal capacity
Northern Lights (Norway)	Operational Phase 1	≥99.9% CO_2; SO_x/NO_x <100 ppm; H_2O <0.2%; O_2 <4%	~15 bar	–27°C	1.5 Mtpa (expandable to 5 Mtpa)
Esbjerg (Denmark)	Demonstration stage (Greensand)	≥95–99% CO_2	LCO_2-compatible pressure ranges	Cryogenic (–30 to –50°C typical)	~0.45 Mtpa early capacity
Immingham (UK)	CCS import terminal in development	≥95–99% CO_2 for pipeline transport	~15–22 bar (pipeline-aligned)	–25°C to –35°C typical	Part of Humber cluster (multi-Mtpa future volumes)
Antwerp-Bruges (Belgium)	Early development	≥95% CO_2 for utilisation/liquefaction hub	LCO_2 standard ranges	Cryogenic	Industrial off-takers; future storage linkage
Dunkirk (France)	Planned	Not yet published; expected ≥95% CO_2	To match LCO_2 envelopes	To match LCO_2 envelopes	Linked to Northern France industrial hub
Wilhelmshaven (Germany)	Announced	Not yet published; expected high purity	As above	As above	Developing as CO_2 import/export hub
Singapore	Conceptual stage	To Be Determined; Regulatory alignment needed	TBD	TBD	Potential APAC transshipment hub

Table 9. Disposal Pathways Available or Planned at These Ports

Port / Hub	Primary Disposal Pathway	Secondary Pathways	Notes
Rotterdam (Porthos)	Offshore geological storage (North Sea)	Power-to-X fuels; industrial utilisation	Europe's largest developing CO_2 network
Northern Lights (Norway)	Offshore saline aquifer storage	None currently	Certified long-term storage with documented chain-of-custody
Esbjerg (DK)	Offshore geological storage (Greensand)	Potential industrial mineralisation	First cross-border offshore storage project
Immingham (UK)	Offshore storage (North Sea)	Industrial use planned	Connected to Humber industrial cluster
Antwerp-Bruges (Belgium)	Industrial utilisation (chemicals, fuels)	Future offshore storage integration	Major P2X hub development
Dunkirk (France)	To-be-developed offshore storage	Industrial clusters (cement, steel)	Early-stage project
Wilhelmshaven (Germany)	Planned offshore storage	P2X possible	Part of Germany's CCS & hydrogen hub strategy
Singapore	TBD	Possible export for offshore storage in partner countries	Requires London Protocol alignment

3.5.4 Global View of Emerging Cross-Border CCUS Ecosystems

In this part of the report, we will focus on the regions shaping the cross-border CCUS Systems and how these regions are developing their cross-border shipping models to bridge the gap between areas of carbon capture and those with abundant sequestration capacity. As illustrated in Figure 56, two key ecosystems for cross-border CCUS are emerging, one in Northwestern Europe and one in the Asia Pacific region.

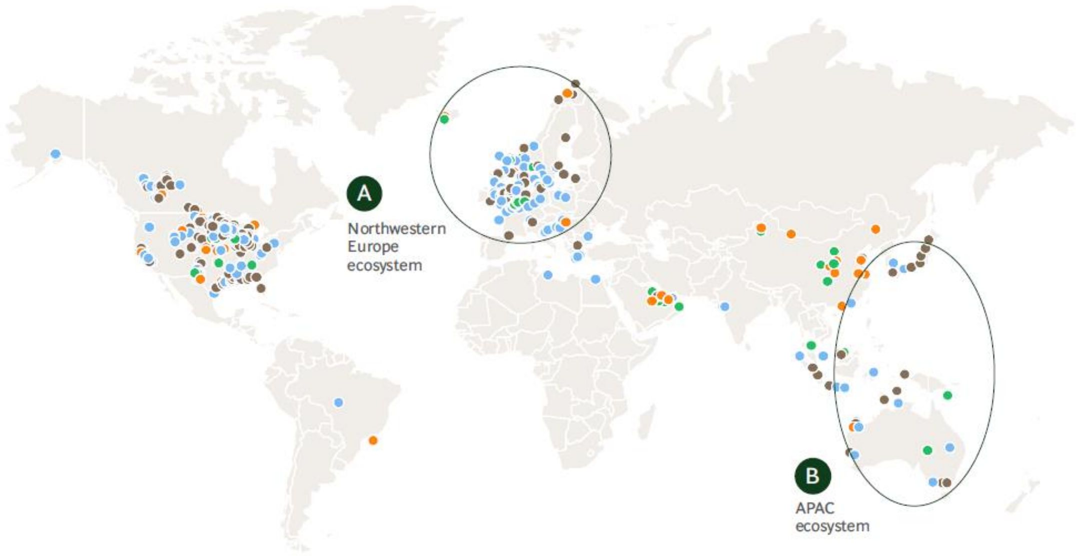


Figure 56. Cross-border CCUS operations (Global Centre for Maritime Decarbonisation, & Boston Consulting Group, 2024)

3.5.4.1 Regions

Northwestern Europe

Northwestern Europe represents the most advanced integrated CCUS ecosystem globally. Offshore storage in the Norwegian, Danish, Dutch and UK sectors of the North Sea is now complemented by a network of capture clusters, port terminals, shared transport infrastructure and multi-user storage hubs. Countries such as Belgium, Germany, Ireland, Sweden and Finland, whose domestic storage is limited or not yet permitted, are positioning themselves as cross-border exporters, relying on shipping to access the expanding storage capacity in Norway, Denmark and the Netherlands. This region is therefore the world's first fully developed capture–terminal–shipping–offshore storage system, supported by strong bilateral agreements, terminal investments, and open-access storage models.

Asia–Pacific (APAC)

The APAC region is characterised by a very large stationary emissions base and relatively uneven distribution of geological storage. Industrial economies such as Japan, South Korea and Singapore face substantial domestic storage constraints, driving the creation of CO_2-export frameworks and bilateral agreements with storage-rich nations such as Australia and Malaysia. Meanwhile, Australia and parts of Southeast Asia are progressing substantial offshore storage sites in well-characterised basins that can support multi-million-tonne storage over the long term. APAC is therefore emerging as the second major global CO_2-shipping ecosystem, driven by necessity, energy security considerations, and early regulatory cooperation.

North America

North America currently relies predominantly on pipeline systems, particularly across the United States, where existing CO_2 networks originally designed for Enhanced Oil Recovery provide a strong basis for industrial capture and onshore saline storage. However, cross-border maritime hubs are beginning to emerge in regions where pipeline connectivity is limited, or offshore disposal is more strategically attractive, such as the Gulf Coast, Eastern Seaboard and Pacific Northwest. Canada is also considering marine corridors to connect eastern industrial centres to western storage. As offshore Gulf of Mexico storage progresses toward FEED and FID, shipping could complement pipeline systems, especially for smaller or more flexible volumes. However, in the US and Canada, pipelines are expected to remain the preferred option driven by the availability of CO_2 sink locations, government incentives and encouragement of domestic CCUS development.

3.5.4.2 Structural Roles and Transport Dynamics in Emerging Cross-Border CCUS Systems

As cross-border CCUS ecosystems mature, differences in geological suitability, industrial structure and regulatory readiness give rise to distinct roles within the global system. Some countries emerge as CO_2 exporters due to limited access to domestic storage, while others develop into storage hubs capable of absorbing international volumes. Parallel to this, the technical and economic characteristics of CO_2 shipping shape decisions on when maritime transport becomes preferable over pipeline connections. Together, these dynamics explain how multi-country CCUS value chains are forming and why shipping is becoming an indispensable element of long-term decarbonisation pathways.

Countries Positioned as CO_2 Exporters

A growing number of industrial economies are structurally predisposed to export CO_2 rather than store it domestically. This trend is most visible in regions where onshore storage faces geological constraints, such as limited saline aquifer suitability, unfavourable reservoir characteristics, or seismic and geotechnical risks that complicate appraisal and permitting. In several countries, public acceptance challenges reinforce these limitations, making onshore geological storage politically sensitive and significantly delaying project timelines. As a result, industrial clusters, particularly those located in coastal areas, are seeking long-term access to offshore storage in neighbouring jurisdictions with better geological endowments.

In addition, the high cost and uncertainty of early-stage domestic storage development further encourages reliance on foreign hubs. Storage appraisal often requires extensive seismic surveys, stratigraphic test wells and regulatory approvals that can extend over many years. For countries with immediate decarbonisation needs or limited technical capacity, accessing already-developed offshore hubs via shipping offers a lower-risk pathway. Finally, several economies have expressed strategic ambition to become regional exporting centres, leveraging their port infrastructure, industrial clusters and maritime capabilities to integrate into global CCUS value chains. This includes nations in both Europe and Asia that view cross-border CO_2 export as an economically attractive means of maintaining industrial competitiveness while meeting climate-aligned emissions targets.

Countries Developing as CO_2 Importing and Storage Hubs

Conversely, countries with abundant, well-characterised offshore geological formations are increasingly positioning themselves as long-term CO_2 storage providers. These regions benefit from extensive subsurface datasets, decades of oil and gas operational experience, and established regulatory frameworks that can be adapted for CCS. As such, they can progress storage development more rapidly and at greater scale than nations with limited geological resources.

Early investment in CO_2 transport and storage infrastructure reinforces this advantage. Several countries have advanced offshore storage projects through FEED and FID stages, creating ready-to-use injection capacity capable of attracting cross-border volumes. The availability of proven reservoirs, combined with expertise in offshore engineering, enables these countries to evolve into regional storage hubs, offering multi-user, open-access services to emitters in surrounding regions. This dynamic is particularly evident in Northwestern Europe, where large saline aquifers and depleted gas fields in the North Sea underpin a rapidly expanding cross-border ecosystem between countries like Norway, Sweden, Denmark and the UK. Similar patterns are emerging in the Asia-Pacific region, where countries with strong offshore competencies are exploring roles as CO_2 import destinations for nearby industrial economies.

The Role of Shipping in Cross-Border CO_2 Transport

Maritime CO_2 transport plays an increasingly decisive role in shaping these emerging ecosystems. Shipping becomes particularly advantageous in situations where long transport distances make pipelines economically prohibitive or technically challenging, especially for offshore routes that require substantial capital expenditure. In such cases, LCO_2 shipping offers a flexible, modular alternative that avoids the need for large upfront investment.

Shipping is also well suited to lower or variable CO_2 volumes, typically below the threshold at which pipelines achieve cost efficiency. This characteristic is critical for early-stage CCS deployment, where capture volumes may fluctuate across sectors and regions. Moreover, maritime transport supports greater destination flexibility, allowing CO_2 cargoes to be redirected as storage hubs mature, contract structures evolve, or new geological capacity becomes available. This adaptability lowers investment risk for both exporters and importers, ensuring that infrastructure can scale progressively as CCS deployment accelerates.

Together, these factors demonstrate why shipping-enabled CCUS networks are central to the long-term viability of cross-border storage solutions. They allow emitters to access high-quality offshore reservoirs, enable storage hubs to aggregate diverse sources of CO_2, and provide the flexibility required to manage uncertainty during the early phases of global CCS adoption.

3.6 Implications for Liner and Tramp Shipping in the CO_2 Value Chain

Liner and tramp shipping represent two distinct operational models within the maritime sector, and these differences have a direct impact on the feasibility, integration challenges, and economic performance of Onboard Carbon Capture and Storage (OCCS) technologies. Liner shipping operates on fixed schedules and predetermined port rotations, whereas tramp shipping is driven by dynamic market demand, sailing irregular routes and calling at a wide variety of ports depending on the charter requirements. These contrasting patterns significantly affect how easily captured CO_2 can be offloaded and how reliably an OCCS installation can be supported during global operations.

Liner vessels benefit from predictable port calls, a factor that greatly facilitates the offloading of captured CO_2 at ports equipped with CO_2 reception and handling facilities. This is particularly important because current studies emphasize that port readiness remains a major barrier to widespread OCCS deployment across maritime trades. In the GCMD assessment (Global Centre for Maritime Decarbonisation, & Boston Consulting Group, 2024), the lack of infrastructure in many ports was highlighted as a key limitation, despite OCCS being technically viable and offering meaningful emission reduction potential. Liner shipping's regular routing therefore provides a structural advantage: operators can strategically select or negotiate port calls at locations that possess the required CO_2 offloading capability. This reduces the risk of exceeding onboard storage capacity, which is a serious operational concern.

The operational profile of liner vessels also tends to align better with the energy demands of many OCCS systems. Chemical absorption technologies, for example, require significant thermal and electrical power for solvent regeneration and CO_2 liquefaction. The Project REMARCCABLE observed a fuel consumption penalty of approximately 15% for a representative amine-based OCCS installation. While this increase is substantial, liner vessels, especially containerships, generally operate with more stable auxiliary power margins and more consistent load profiles than tramp carriers, making it easier to accommodate these demands without compromising schedule reliability. Although container ships face physical constraints due to limited superstructure and deckhouse volume, these challenges are more easily addressed in newbuilding designs where OCCS can be integrated from the outset.

In contrast, tramp shipping faces much greater complications. Tramp vessels such as bulk carriers and tankers call at an unpredictable mix of ports worldwide, many of which lack any capability to receive, handle or transport captured CO_2. As a result, CO_2 must be safely stored on board until a suitable port is available to accept it, and this requirement directly affects ship design, machinery integration and storage capacity. Because tramp operators cannot be certain that the next port will provide CO_2 offloading infrastructure, they face a heightened risk of filling their storage tanks while still at sea, particularly on long haul trades where deadweight, tank volume and stability considerations quickly become binding constraints. Retrofits can impose substantial deadweight penalties and create feasibility concerns owing to the space and weight requirements of capture equipment and storage systems, which is especially challenging for vessels whose commercial performance depends on maximising cargo intake.

Additionally, specific bulk carriers and cement carriers offer large deck and hold volumes that can support alternative OCCS technologies such as calcium looping, where CO_2 reacts with CaO to produce solid $CaCO_3$. This approach eliminates the need for cryogenic liquid CO_2 tanks and has already been demonstrated commercially. Seabound's deployment of calcium looping technology on the UBC Cork, a cement-carrying vessel, illustrated the feasibility of capturing CO_2 at high efficiency and storing it as limestone, which can be offloaded directly to an industrial partner. This model is particularly compatible with tramp trades that connect regularly with industrial facilities such as cement plants, refineries, or mining operations, even if global CO_2 terminals remain sparse.

In summary, liner shipping is generally better positioned to adopt OCCS because its predictability enables reliable CO_2 offloading, planned energy allocation, and structured integration into vessel operations. For tramp shipping, OCCS adoption is heavily influenced by cargo type, space availability, and access to ecosystems capable of receiving captured CO_2. While technological options exist for both sectors, their differing operational realities mean that OCCS solutions must be carefully tailored to each ship type and trade pattern to ensure technical success and commercial viability.

4. Regulatory Review

The availability of a clear and robust regulatory framework for the offloading of CO_2 from ships is a critical prerequisite for the inclusion of onboard carbon capture within the wider CCUS value chain and its seamless transfer to onshore and offshore storage and/or utilisation facilities. In the absence of such regulatory clarity, the development, deployment, and commercialisation of OCCS risk being delayed or constrained, despite their potential contribution to near-term GHG abatement in shipping.

It should be noted that although onboard carbon-capture pathways that produce liquefied CO_2 face complex regulatory requirements for offloading, cross-border transport, and permanent storage, these constraints do not generally apply to calcium carbonate ($CaCO_3$) produced through mineralisation-based OCCS. $CaCO_3$ is a stable, non-hazardous industrial mineral widely traded across global markets and typically handled under standard bulk-cargo or containerised-cargo procedures. Because it is not regulated as a waste stream under marine dumping rules, nor classified as hazardous waste under the Basel Convention, its movement between ports normally proceeds under conventional commercial and customs frameworks. As a result, the $CaCO_3$ pathway avoids most of the regulatory friction associated with LCO_2 logistics and presents a comparatively straightforward route for offloading, transport, and terrestrial utilisation or disposal. Taking the above into consideration, the regulatory analysis focuses on the capture, storage, transportation and disposal of CO_2.

Against this backdrop, this Regulatory Review assesses the current state of regulatory readiness for OCCS, with particular emphasis on the offloading, transport, and downstream handling of captured CO_2. Particular attention is given to how environmental regulation and decarbonisation policy frameworks address (or currently fail to address) the treatment of captured CO_2 in relation to emissions reporting, lifecycle assessment, monitoring, reporting and verification (MRV) requirements, and eligibility under market-based measures. The review follows a structured approach, progressing from global maritime regulations to regional and national frameworks, before examining the international environmental conventions that bind these regimes together and concluding with a synthesis and forward-looking assessment.

The analysis begins with a review of the International Maritime Organisation (IMO) regulatory framework relevant to OCCS, including the International Convention for the Prevention of Pollution from Ships (MARPOL), the International Convention for the Safety of Life at Sea (SOLAS), and evolving IMO GHG measures, to assess how onboard carbon capture is currently treated within international shipping regulations. Consideration is also given to the development of mid-term GHG reduction measures, including technical and economic elements, and the extent to which captured CO_2 may be accounted for within the IMO Data Collection System (DCS) and any future global fuel standard or carbon pricing mechanism. The interaction between OCCS and short-term ship energy efficiency requirements, such as EEXI/EEDI and CII, is also examined from both a regulatory and compliance perspective.

The review then examines regional regulation, with a focus on the European Union, where climate and industrial policy instruments may directly and indirectly influence OCCS deployment. These include the EU Emissions Trading System (EU ETS), the FuelEU Maritime Regulation, and the Monitoring, Reporting and Verification (MRV) Regulation, all of which raise critical questions regarding the recognition of captured and permanently stored CO_2, allocation of compliance responsibilities, and the treatment of negative or avoided emissions. The role of economic incentives, carbon pricing signals, innovation funding mechanisms, and potential access to carbon crediting frameworks is analysed to determine whether OCCS can achieve regulatory recognition and financial viability within existing decarbonisation architectures. Broader policy linkages to the EU CCS Strategy and trans-European CO_2 transport infrastructure planning are also considered.

To provide practical insight into regulatory readiness, the report presents findings from a high-level review of policy and regulatory frameworks in the UK, EU Member States, the United States, and Asian nations such as Singapore, China, and Japan, selected based on their potential for early CCS and liquefied CO_2 (LCO_2) offloading infrastructure development. Particular emphasis is placed on national carbon pricing regimes, tax credit schemes, storage licensing frameworks, and liability provisions governing long-term CO_2 sequestration. In addition, domestic regulatory frameworks in the Netherlands, Denmark, Germany, and France (as part of the European Economic Area) are examined to provide further regional context, especially in relation to cross-border CO_2 transport and storage cooperation. The review is based on the most up-to-date information available at the time of preparation (January 2026).

The review further considers international environmental conventions, notably the London Convention and London Protocol, which govern the transboundary movement and disposal of CO_2 and play a central role in enabling or constraining cross-border CO_2 transport by ship. The Basel Convention adds a further layer of complexity, as its applicability depends on whether captured CO_2 is considered a "waste" or "hazardous waste" by any state involved in a cross-border chain. The compatibility of maritime CO_2 offloading operations with international environmental law, including provisions on waste classification, marine pollution prevention, and sub-seabed storage, is assessed in order to clarify the legal status of captured CO_2 once it leaves the vessel.

In parallel, the role of classification societies is addressed, recognising their importance in translating high-level regulatory principles into technical requirements for OCCS design, approval, installation, and safe operation. Existing class rules, provisional guidelines, and risk-based approval frameworks for carbon capture systems, CO_2 handling, liquefaction, storage, and transfer operations are examined, together with their interface with flag State requirements and port State control. The evolving technical standards issued by leading classification societies are considered a critical bridge between regulatory intent and practical shipboard implementation, particularly in the absence of fully harmonised international rules.

Finally, the report synthesises the findings to identify regulatory gaps, areas of convergence, and emerging trends, and provides a strategic outlook on how OCCS-related regulation may evolve in the coming years. This includes consideration of the potential integration of OCCS within global and regional market-based measures, the development of harmonised CO_2 accounting and crediting methodologies, the clarification of liability and chain-of-custody provisions across the CCUS value chain, and the progressive codification of class and safety standards. The outlook reflects ongoing developments at IMO, regional policy initiatives, and increasing public and private investment in CCS infrastructure globally, all of which will shape the pace and scale at which OCCS can contribute to maritime decarbonisation.

4.1 OCCS in the IMO Regulatory Landscape

The International Maritime Organisation (IMO) has established the overarching policy direction for shipping decarbonisation through its revised GHG framework, most recently articulated in the 2023 IMO Strategy on Reduction of GHG Emissions from Ships. The Strategy sets out a strengthened ambition to reach net-zero GHG emissions from international shipping by or around 2050, with indicative checkpoints of at least 20% (striving for 30%) absolute emission reductions by 2030 and at least 70% (striving for 80%) by 2040, compared to 2008 levels. In parallel, it confirms the existing carbon intensity targets of reducing CO_2 emissions per transport work by at least 40% by 2030 (compared to 2008) and promotes the uptake of zero- or near-zero GHG fuels, technologies, and energy sources to account for at least 5% (striving for 10%) of energy used by international shipping by 2030. To deliver these objectives, the IMO proposed a basket of mid-term measures, expected for adoption in 2025 and entry into force around 2027, combining a technical element (likely a global fuel standard regulating lifecycle GHG intensity) and an economic element (a market-based measure such as a carbon pricing mechanism). The adoption of the net Zero Framework (NZF) has been adjourned for a year due to the objections of several UN member states. At the moment, the future developments of NZF are unclear.

For OCCS, this evolving framework is highly relevant: its viability will depend on whether captured and permanently stored CO_2 can be recognised within IMO accounting rules, reflected in compliance calculations under future fuel standards, and potentially credited or incentivised under any global carbon pricing regime. Even though OCCS is currently not explicitly regulated under the IMO framework, it is increasingly referenced and formally acknowledged within ongoing IMO discussions on maritime decarbonisation. Its regulatory treatment is evolving alongside the development of the IMO's mid and long term Strategy and associated compliance mechanisms, particularly the Global Fuel Standard (GFI) and lifecycle-based accounting methodologies.

4.1.1 IMO Greenhouse Gas Fuel Intensity (GFI) regulation

The proposed IMO Greenhouse Gas Fuel Intensity (GFI) regulation forms the technical pillar of the Organisation's mid-term GHG measures under the 2023 Strategy and is expected to establish a global fuel standard for international shipping. The GFI mechanism will set progressively tightening limits on the lifecycle GHG intensity (well-to-wake) of marine energy used onboard ships, expressed in grams of CO_2-equivalent per unit of energy by applying two compliance limits, the "Base" and the "Direct" limit. Compliance would be assessed annually, with ships required to meet declining intensity thresholds over time, thereby driving the uptake of low- and zero-carbon fuels, alternative energy sources, and potentially abatement technologies such as OCCS, subject to agreed accounting methodologies. Failure to comply with the GFI limits will induce financial penalties of varying magnitude based on the time of non-compliance (Tier I and Tier II penalties). Within this framework, fuels and energy sources meeting very low lifecycle emission criteria are commonly referred to as Zero- or Near-Zero (ZNZ) GHG fuels. While final thresholds remain under negotiation at the International Maritime Organisation, ZNZ fuels are expected to include options such as green hydrogen, green ammonia, advanced sustainable biofuels, and certain e-fuels that demonstrate minimal lifecycle emissions. The GFI regulation is intended to create a predictable decarbonisation trajectory toward 2050, while potentially interacting with an accompanying economic measure.

For OCCS, a critical issue in order to contribute to reductions in the average global GHG intensity of vessels is whether the impact of carbon capture is formally incorporated into fuel life-cycle assessment methodologies. The IMO has indicated that Zero or Near-Zero (ZNZ) rewards are expected to target fuels, energy sources, or technologies assessed on a Well-to-Wake (WtW) basis, with a primary focus on the intrinsic GHG intensity of the energy source itself. As Zero or Near Zero technologies are considered the ones able to reduce the GHG intensity of a fuel down to 19 gCO_2/MJ of delivered energy. This threshold is expected to be decreased down to 14 gCO_2/MJ after 2035 (MEPC.83, 2025). A schematic representation of the GFI "Base" and "Direct" limit and ZNZ reward threshold can be seen in Figure 57. The GHG intensity of common marine fuels is given with continuous lines, while the GHG intensity of the same fuels is recalculated after assuming a 30% OCC capture rate. This highlights the potential impact of OCCS as a GHG abatement technology for the IMO NZF framework.

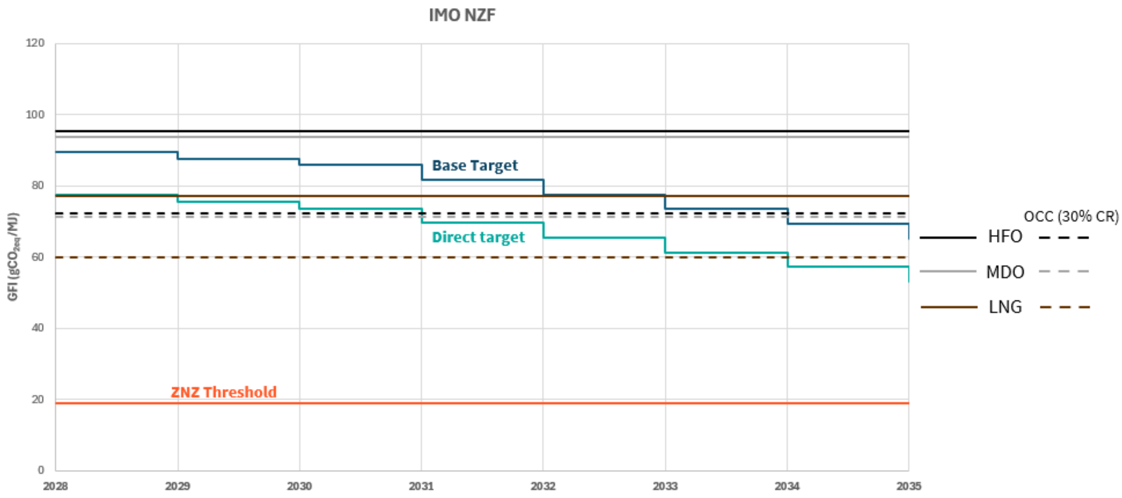


Figure 57. Graphic representation of NZF limits and the impact of OCC (30% CR) on common marine fuels

Nevertheless, OCCS may be recognised as a transitional decarbonisation pathway, provided that strict conditions are met. These conditions include the demonstration of permanent CO_2 removal, robust lifecycle accounting, clear liability allocation, and verified chain-of-custody from capture to final storage or utilisation. Within IMO discussions, carbon capture and storage is referenced as a potentially eligible technology under future compliance mechanisms, but it remains methodologically undefined at this stage.

A significant regulatory milestone was reached with the agreement on a Work Plan for the development of a regulatory framework for the use of OCCS, which has been adopted by the Marine Environment Protection Committee (MEPC). This work plan aims to establish the necessary regulatory, safety, and accounting provisions for OCCS and is scheduled to be finalised by 2028. The work programme covers issues such as certification, enforcement, traceability of captured CO_2, compatibility with reception facilities, and environmental safeguards.

At the same time, the implementation of the GFI measure has been adjourned, introducing uncertainty regarding the timing and manner in which OCCS may be integrated into future IMO compliance schemes. This delay reinforces the current status of OCCS as a concept accepted in principle but not yet supported by finalised accounting rules or incentive mechanisms.

In summary, within the IMO regulatory landscape, OCCS is recognised as a promising but provisional decarbonisation option. Its future eligibility under IMO instruments will depend on the successful development of lifecycle accounting methodologies, the demonstration of permanent emissions removal, and alignment with international legal frameworks governing CO_2 transport, storage, and environmental protection.

4.1.2 Lifecycle Accounting & LCA Guidelines

The development and finalisation of the IMO Life Cycle Assessment (LCA) Guidelines represent a critical enabling factor for the regulatory recognition and potential incentivisation of OCCS. The LCA framework under development will determine how GHG emissions are accounted for across the full fuel lifecycle and, consequently, whether captured CO_2 can be credited as a legitimate emissions reduction under future IMO compliance mechanisms, including the GHG Fuel Intensity (GFI) framework.

A key update in these guidelines is the introduction of the Emission Credit concept for e_{OCCS}. In particular, paragraph 5.2 of MEPC.391(81) integrates e_{OCCS} into the TtW emission factor calculation, recognizing that onboard CO_2 capture and long-term storage could contribute to reducing emissions. However, the methodological approach for e_{OCCS} is still under development, and current guidance specifies that the e_{OCCS} value must remain zero until further notice (MEPC.391(81), 2024). It is noted that in theory e_{OCCS} is designed to account for the emissions avoided through the capture and sequestration of emitted CO_2 when OCCS occurs on board. This should include the equivalent of the CO_2 emissions that were not released to the atmosphere minus the emissions associated with the process of capturing, compressing and temporarily storing on board, emissions associated with the transport to long-term storage site, emissions associated the process of storing including fugitive emissions and any other additional emissions related to the CCS. It is noted that e_{OCCS} is designed to account directly for CO_2 emissions that are restricted from release to the atmosphere.

At present, the IMO LCA Guidelines remain under development and are primarily fuel-centric, focusing on emissions associated with energy carriers rather than shipboard abatement technologies. The framework distinguishes between Well-to-Tank (WtT) emissions, covering fuel production and supply, and Tank-to-Wake (TtW) emissions, representing CO_2 released during onboard combustion. Under the current methodological assumptions, CO_2 emissions are considered to occur at the point of combustion and are treated as final, unless they are permanently removed within the defined system boundary. This assumption creates a structural challenge for OCCS, as captured CO_2 is not automatically recognised as an avoided emission unless its subsequent handling, transport, and permanent storage can be robustly demonstrated and verified.

The IMO has acknowledged that the existing LCA framework was not sufficiently mature to fully integrate OCC-related considerations at the time of its development. As a result, no default emission factors or accounting rules have been established for onboard carbon capture, and OCC-specific parameters remain either unresolved or provisionally bracketed. MEPC discussions have nevertheless recognised the need for the LCA framework to address OCC explicitly, in order to ensure that CO_2 captured at sea is fully and consistently accounted for across the value chain. However, as of today, no finalised methodology exists, and OCC remains effectively outside the original fuel lifecycle logic, requiring a methodological expansion of the LCA framework.

Several key challenges must be addressed before OCCS can be reliably credited under the IMO LCA regime. First, robust measurement, documentation, and verification procedures are required to quantify captured CO_2 and establish traceability from onboard capture through offloading, reception, and final storage or utilisation. Second, the framework must ensure prevention of atmospheric re-release, as any venting or leakage during onboard storage, offloading, or shore-side handling would undermine the environmental integrity of OCC and invalidate LCA crediting. Third, clear criteria must be established to distinguish between permanent storage and utilisation pathways, as only CO_2 that is permanently stored or demonstrably removed from the atmosphere can be considered a genuine emissions reduction for LCA purposes.

In addition, the LCA methodology will need to address the adjustment of Tank-to-Wake emissions following OCC operation, ensuring that claimed reductions reflect net emissions after accounting for the additional energy consumption associated with capture, solvent regeneration, compression, liquefaction, and auxiliary power demand. Capture efficiency and system performance therefore become critical parameters in determining the true climate benefit of OCCS.

Until these issues are resolved and the LCA Guidelines are finalised, OCCS cannot be reliably credited under the IMO LCA framework, limiting its eligibility under future market-based measures and financial incentive schemes. While technology is widely regarded as technically promising, its regulatory status remains provisional, with investment certainty and commercial deployment strongly dependent on forthcoming methodological clarifications at IMO level.

4.1.3 Potential impact of OCCS on IMO short-Term measures

Interaction with EEDI Energy Efficiency Existing Ship Index) and EEXI (Energy Efficiency Existing Ship Index)

The EEDI (applicable to vessels contracted after 2013 or delivered after 1st July 2015) and EEXI (applicable to pre-existing vessels) are a set of technical, design-based indices intended to regulate the energy efficiency performance of ships under defined reference conditions. It is calculated ex-ante and reflects the vessel's by-design characteristics, including installed engine power, reference speed, fuel type and the presence of approved energy-efficiency technologies (MEPC.308(73), 2018) (MEPC.333(76), 2021). Importantly, EEDI/EEXI does not rely on operational data, fuel consumption records, or measured emissions, and therefore does not currently account for post-combustion emission treatment technologies.

Under the existing regulatory framework, OCCS is not recognised as an eligible technology within the EEDI/EEXI calculation methodology. This implies that, in the absence of a formal regulatory pathway to account for the removal of post-combustion CO_2 emissions, the installation of an additional mechanical system such as an onboard carbon capture system (OCCS) may have adverse compliance implications. Since OCCS increases onboard energy demand (and therefore, fuel consumption), its installation could negatively affect a vessel's attained EEXI value. For certain ships, this may result in an EEXI penalty or reduce the available compliance margin under existing Engine Power Limitation (EPL) or Shaft Power Limitation (ShaPoLi) arrangements.

For OCCS to be accounted for under EEDI/EEXI, it would be necessary for carbon capture systems to be formally introduced into the EEXI Calculation Guidelines as an approved efficiency or emissions-reduction technology. This would require the development of agreed assumptions regarding the theoretical "by-design" capture performance of OCCS systems under reference operating conditions, consistent with the conceptual structure of EEXI. One notable pathway for the inclusion of OCCS impact into the EEDI/EEXI framework would be through the creation of a dedicated correction factor, capturing the systems designed technical specifications and operational efficiency.

In principle, OCCS could be considered at the design stage as part of a ship's energy and emissions architecture, provided that its performance is defined independently of operational variability. However, such inclusion would require explicit regulatory amendments, including the definition of capture efficiency parameters, boundary conditions, and interactions with auxiliary power demand. It should be noted however that the additional energy demand associated with capture, compression, and storage systems should also be reflected in the updated calculation methodology.

Interaction with CII (Carbon Intensity Indicator)

Unlike EEDI and EEXI, the Carbon Intensity Indicator (CII) is an operational metric based on annual fuel consumption data collected under the IMO Data Collection System (DCS). CII reflects the relationship between a ship's transport work and its total CO_2 emissions, calculated using fuel consumption multiplied by prescribed carbon factors. The calculation of the annual CII is based on data collected according to the IMO DCS (Data Collection System). At the current stage, there is no formal mechanism under DCS to reflect post-combustion carbon removal in reported emissions. In this regard, CII represents gross CO_2 emissions at the point of combustion, with no mechanism to recognise captured, stored, or offloaded CO_2. As OCCS becomes more prevalent however, it will be important to determine how captured emissions are reflected in CII calculations. This could involve custody transfer systems, direct measurements, or alternative accounting methods to ensure fair and accurate reporting Additionally, during the vessel's operational stage, the CII would provide ongoing assessment and incentives for maintaining low emissions.

From a technical perspective however, CII offers a clearer conceptual pathway for potential OCCS recognition. Captured CO_2 quantities could, in principle, be deducted from the CII numerator, provided that robust methodologies for measurement, verification and certification are established. Such an approach would require captured CO_2 volumes to be aggregated over the reporting period, independently verified, and supported by documentation from authorised reception or offloading facilities. Certification could be linked to mass balance records, custody transfer documentation, and confirmation of subsequent storage or utilisation. The CII calculation is primarily based on the Ship Energy Efficiency Management Plan (SEEMP) regulation. While SEEMP does not directly mandate the use of OCCS systems, it provides a regulatory and strategic framework that supports their adoption.

However, the current CII regulatory framework does not permit such deductions. Amendments would be required to MARPOL Annex VI and the associated DCS and CII Guidelines to define captured CO_2 as a reportable parameter and to establish the conditions under which it may be deducted from reported emissions. Key issues would include avoidance of double counting, treatment of temporary storage, and assurance of environmental integrity.

Conceptual CII development for OCCS accounting

The existence of multiple correction factors within the CII framework demonstrates that the IMO has already recognised the need to adjust the CII numerator in cases where emissions are real but structurally misrepresented or unfairly attributed (MEPC.355(78), 2022). These correction factors provide a regulatory precedent that could support future inclusion of OCCS, particularly given that CII is an operational index designed to evolve alongside technological and operational developments. The inclusion of a dedicated factor to the CII calculation formula would be the most straight forward way to allow for the inclusion of OCCS in the CII calculation. A potential OCCS updated CII formula can be seen in Figure 58. Other ways address the OCCS integration would be through the creation of a dedicated correction factor stemming from the technical characteristics of the CCS system or through voyage adjustments while the system is operating.

Sum of total quantity of CO_2 captured annualy and officially verified through a certificate

$$\frac{\sum_j C_j \times \left\{FC_j - \left(FC_{voyage,j} + TF_j + (0.75 - 0.3y_i) \times \left(FC_{electrical,j} + FC_{boiler,j} + FC_{others,j}\right)\right)\right\} + f_{occs}}{f_i \times fm \times fc \times fiVSE \times Capacity \times (Dt - Dx)}$$

Figure 58. Potential update to the CII formula to allow Captured CO_2 deduction

For OCCS to be formally recognised, several enabling conditions must first be satisfied. CO_2 capture onboard must be measurable, verifiable and consistently reported, requiring amendments to the DCS and he SEEMP Part II regulatory framework (MEPC.401(83), 2025). Importantly, DCS already allows for direct CO_2 measurement, which is particularly relevant for pre-combustion systems (MEPC.346(78), 2022). All captured and offloaded CO_2 would need to be fully audited through verification at reception facilities and through documented certificates. Annual aggregation of total captured quantities, combined with evidence of permanent storage or eligible utilisation, would be required to claim reductions.

The practical pathway for incorporating OCCS into CII would rest on a three-pillar monitoring and verification chain.

1. Onboard monitoring would rely on continuous mass-flow measurement at the OCCS outlet leading either to an LCO_2 tank or a solid-carbon container. Key operational parameters (capture

hours, capture rate, solvent or sorbent make-up, alarms and venting etc) need to be logged and cross-checked against DCS noon reports and fuel consumption data.

2. Reception facilities would perform custody-transfer metering or weighbridge measurements for containerised solids and issue a CO_2 Receipt & Custody-Transfer Certificate for every offload event.
3. Downstream operators would provide a Statement of Verified Permanent Storage (SVPS) or a Statement of Eligible Utilisation (SEU), confirming that the CO_2 is either permanently stored or used in an application that does not return it to the atmosphere.

To operationalise this process, IMO would need to amend or supplement several existing regulatory instruments. MARPOL Annex VI Regulation 27 would need new data fields covering CO_2 captured onboard, quantities delivered to reception facilities, and associated certificate identifiers. SEEMP Part II and Part III would require an OCCS-specific MRV annex. The DCS database and reporting formats must also be updated with validation fields for capture-related data. Additionally, new IMO guidance would be required, possibly including a standard certificate format for custody-transfer, guidelines for reception facilities, and a dedicated OCCS MRV Technical Code setting out metrology, calibration, uncertainty bounds and integrity requirements.

Two potential routes exist for submitting a petition to the IMO to begin this regulatory process. The preferred path would be through a Member State, by securing a sponsoring administration willing to table a submission to MEPC or ISWG-GHG proposing amendments to the CII Guideline. Alternatively, an NGO or IGO with IMO consultative status (such as ICS, BIMCO or INTERTANKO) could co-submit the proposal. Both pathways require a structured submission in line with IMO's circular MSC-MEPC.1/Circ.4/Rev.4, outlining the problem, the proposal, impacts and the actions requested.

Indicative Timeline for Petition Submission and Regulatory Adoption

A theoretical adoption timeline suggests that, if industry stakeholders initiate the process promptly, an OCCS correction factor within the CII framework could be implemented in time for the 2030 CII rating cycle.

The process would begin at MEPC 85, where a sponsoring Member State or NGO would submit a concept paper introducing OCCS accounting within CII and requesting the Correspondence Group and ISWG-GHG to draft the required monitoring methodologies and reporting modifications for DCS and SEEMP. By late 2026, the working groups could reach consensus on the scope and structure of the required amendments, enabling the launch of a voluntary pilot program in 2027. During this pilot year, participating ships would report OCCS-related data in parallel with standard DCS submissions. The IMO Secretariat would test new GISIS fields, while Recognised Organisations would verify pilot data as part of SEEMP III audits.

At MEPC 86, the committee could consider draft amendments to the CII Guidelines and the DCS reporting framework, followed by approval for adoption. Formal adoption could realistically occur at MEPC 87 in 2028. Most IMO amendments enter into force after a two-year period, so a captured-CO_2 correction factor could become fully operational by 2029/2030, allowing OCCS deductions to be applied to the 2030 CII rating at the latest. An indicative timeline of regulatory adoption can be seen in Figure 59.

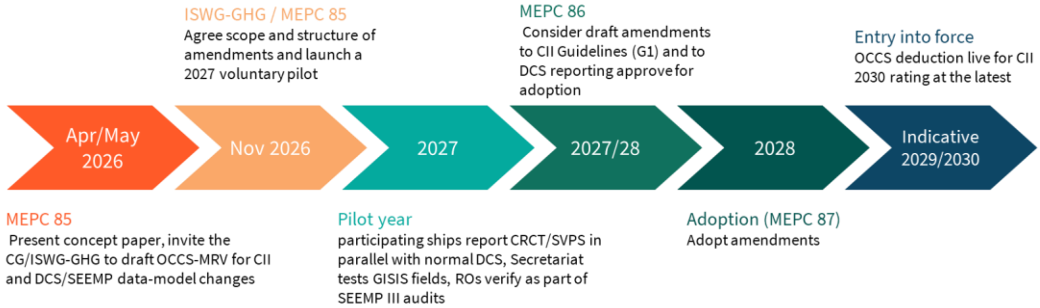


Figure 59. Theoretical Timeline of Petition Submission for OCCS Adoption CII

In summary, while OCCS is not currently accounted for under either EEDI, EEXI or CII, the operational nature of CII and the established use of correction factors suggest that future recognition of OCCS within the CII framework would represent a logical and proportionate regulatory evolution, subject to the development of appropriate methodologies and safeguards. MARPOL Annex VI provides for the review of the EEXI and CII regulations, with a comprehensive review, in accordance with Regulation 28.11 of Annex VI, in conjunction with the review of the CII framework. This review presents a potential opportunity for consideration of emerging technologies such as OCCS, should sufficient technical maturity and consensus on methodology be achieved.

4.1.4 Safety & Environmental Interfaces

The deployment of onboard carbon capture systems (OCCS) introduces a set of safety and environmental considerations that intersect with multiple existing IMO conventions and codes, despite OCCS not being explicitly regulated as a standalone technology. From a regulatory perspective, OCCS is currently treated through analogy with existing shipboard systems, chemical processes, and the carriage of hazardous substances, resulting in a fragmented but evolving compliance landscape.

From a safety standpoint, OCCS incorporates several high-risk elements already addressed under IMO safety instruments, including pressurised systems, chemical absorption processes, additional rotating machinery, and cryogenic or refrigerated CO_2 storage. As such, OCCS is generally considered to fall under the scope of essential shipboard machinery, triggering requirements related to design approval, redundancy, and failure tolerance. Fire, explosion, and containment risks must be systematically assessed, and safety equivalence with conventional machinery systems must be demonstrated to the satisfaction of the flag Administration and the classification society.

SOLAS

Under the International Convention for the Safety of Life at Sea (SOLAS), particularly Chapter II-1 and Chapter VII, the presence of hazardous substances and complex process equipment onboard requires compliance with applicable international codes. Captured CO_2, when stored in liquefied or refrigerated form, aligns with existing classifications under the International Maritime Dangerous Goods (IMDG) Code, where carbon dioxide is designated as UN 2187 (Carbon dioxide, refrigerated liquid). Where CO_2 is handled in bulk, relevant provisions of the IBC Code or IGC Code may also become applicable, depending on storage conditions, quantities, and system configuration.

In the absence of prescriptive OCC-specific regulations, approval pathways currently rely on risk-based and goal-based approaches, such as Alternative Design and Arrangements under SOLAS Regulation II-1/55. This requires a holistic safety case demonstrating that OCCS achieves an equivalent level of safety to conventional ship systems, supported by hazard identification (HAZID), hazard and operability (HAZOP) studies, failure mode analyses, and emergency response planning. Particular attention is required for interfaces between OCCS and existing ship systems, including engine exhaust integration, power supply, ventilation, fire detection, and control systems.

IBC Code

The International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk or also references as International Bulk Chemical (IBC) sets out the global standard for the safe maritime transport of dangerous chemicals and noxious liquid substances. These substances, listed in Chapter 17 of the Code, require specialised ship design, construction features, and equipment to ensure that carriage by sea poses minimal risk to the ship, its crew, and the marine environment (IMO-IBC Code, 2007).

The IBC Code prescribes detailed requirements for ship structure, cargo containment systems, cargo-handling arrangements, protective equipment, and operational procedures. These requirements are based on the physical and chemical characteristics of the substances being transported, ensuring that the hazards associated with toxicity, reactivity, pollution potential, and flammability are systematically controlled during bulk carriage. Although the IBC Code does not apply directly to the bulk transport of captured CO_2, it becomes relevant to Onboard Carbon Capture and Storage (OCCS) in two specific ways:

1. Carriage of Chemical Solvents Used in OCCS Systems: OCCS installations frequently use chemical absorbents such as Mono-ethanolamine (MEA). MEA is a listed substance under the IBC Code, and therefore its transport must comply with the appropriate IBC Code requirements. In this context, the Code provides guidance on containment, material compatibility, pollution prevention, ventilation, and safe-handling measures for MEA. However, the "Concept Study of Offloading Onboard Captured LCO_2 (2024)" notes that solvent carriage is outside the scope of that particular study, which focuses solely on the offloading of captured carbon dioxide rather than associated chemical inventories.
2. Classification of Packaged or Non-Bulk LCO_2 for Offloading Operations: While liquefied CO_2 (LCO_2) is not categorised as a bulk chemical under the IBC Code, the study highlights that LCO_2 would qualify as a Hazardous Material under Class 2.2 (non-flammable, non-toxic gases). This classification also aligns with the Globally Harmonised System (GHS) for chemical hazard communication.

IGC Code

The International Gas Carrier (IGC) Code applies to ships that transport liquefied gases with a vapour pressure above 2.8 bar at 37.8°C, as well as other substances listed in Chapter 19. It sets out the design, construction, and equipment requirements for such vessels. In the context of onboard carbon capture and storage (OCCS), the IGC Code is especially relevant because captured CO_2 may need to be stored onboard in liquefied form. The Code therefore provides essential guidance for the safe storage and transfer of liquefied CO_2 (LCO_2), particularly when using Type C independent tanks (IMO-IGC Code, 1986).

Storing LCO_2 introduces several key risks, including respiratory hazards, cryogenic burns, exposure to extremely low temperatures, and the potential for asphyxiation. Additional considerations include the material challenges posed by CO_2's triple point, tank construction integrity, safe transfer procedures, and the possibility of structural damage or BLEVE (Boiling Liquid Expanding Vapour Explosion). Risks to personnel must also be taken into account.

To address these hazards, proposed updates to the IGC Code seek to enhance safety by incorporating advanced monitoring systems for CO_2 cargoes. These improvements focus on better understanding thermodynamic behaviour, maintaining stable pressure conditions, and managing impurities to avoid solidification or structural failures during transport.

IMDG Code

The International Maritime Dangerous Goods (IMDG) Code establishes the global framework governing the maritime transport of dangerous goods in packaged form. Its purpose is to harmonise safety requirements across international shipping by defining standards for packaging, labelling, placarding, marking, stowage, segregation, handling, and emergency response, while ensuring that dangerous goods are carried in a way that minimises pollution risks. The Code incorporates mandatory provisions set out in Chapter VII of SOLAS for packaged dangerous goods and provides detailed instructions for each substance listed, including requirements for container traffic, stowage arrangements, and the segregation of incompatible cargoes. In the context of onboard carbon capture and storage (OCCS), the IMDG Code does not apply to bulk liquefied CO_2 offloading. However, it becomes directly relevant whenever captured CO_2 is stored and discharged in packaged form, specifically in ISO tank containers. These requirements govern the preparation, handling, and documentation associated with packaged LCO_2, ensuring internationally recognised standards are met during transport and offloading operations.

MARPOL

Under MARPOL Annex I, any risk of accidental discharge of captured CO_2, solvents, or process residues must be addressed as a pollution prevention matter. Furthermore, unintended releases of CO_2 to the atmosphere may fall within the scope of MARPOL Annex VI, which governs air emissions from ships, particularly if such releases undermine claimed emissions reductions or lead to non-compliance with emission limits or reporting obligations. This creates a direct regulatory linkage between OCCS operational integrity and emissions compliance under IMO instruments.

At the environmental interface, the regulatory treatment of captured CO_2 remains conditional on its subsequent handling. While onboard capture itself may reduce direct emissions, any leakage during storage, offloading, or transfer to shore-based facilities risks invalidating environmental benefits and may trigger compliance concerns under both IMO conventions and regional environmental regimes. As such, containment integrity and monitoring are central to both safety assurance and environmental credibility. The maturity level of different Safety and Environmental regulations, affecting the integration of OCC systems has been analysed and maturity rating has been assigned to each regulation, ranging from (no sufficient regulatory framework for OCC) to (Solid existing regulatory framework). Intermediate ratings imply that the regulatory framework is under development or that existing regulations for Onshore CCS may be applied (GCMD, 2025). An analysis covering the OCC-relevant frameworks of IMO like SOLAS, IBC Code, IGC Code, IMDG code and MARPOL can be seen in Table 10.

Table 10. OCC relevant Regulatory Framework maturity analysis

Regulatory framework	Comments	Maturity level
International Convention for the Safety of Life at Sea (SOLAS)	Relevant certifications are a prerequisite for all OCC related systems. No explicit regulation for OCCS. No direct objection against offloading LCO_2 in cargo ports.	
International Bulk Chemical (IBC) Code	LCO_2 is classified as a Hazardous Material under Class 2.2, identifies as Non-flammable nor poisonous cryogenic gas/liquid. This creates a specific pathway.	
The International Code Liquefied Gases Carriege in Bulk (IGC Code)	Chapter 19 of the IGC code provides a list of gases requiring an international certificate of fitness. CO_2 is listed under the code as an asphyxiant.	

International Maritime Dangerous Goods Code (IMDG)	Apply to offloading of LCO_2 in ISO tank containers. providing a route to international regulation offload of packed onboard-captured CO_2 in the form of LCO_2.	
International Convention for the Prevention of Pollution from Ships (MARPOL)	Annex III potentially applies to the transportation of LCO_2 in packaged form (including ISO Tank containers). Likely to require an amendment (e.g. Annex III or VI) to cover offloading of bulk LOC_2.	

Overall, the current regulatory framework addresses OCCS indirectly through existing safety and pollution prevention instruments, rather than through dedicated rules. While this allows early-stage deployment through case-by-case approvals, it also creates regulatory uncertainty and inconsistency across jurisdictions. The development of harmonised OCC-specific safety and environmental guidance at IMO level would therefore significantly enhance regulatory clarity, facilitate broader adoption, and reduce approval risks for shipowners and technology providers.

4.1.5 IMO Status Overview, Evaluation, and Trajectory

The International Maritime Organisation (IMO) has formally acknowledged onboard carbon capture systems (OCCS) as a potentially relevant emissions abatement technology. However, the regulatory framework governing their recognition and integration remains under development and largely provisional. At present, OCCS is not explicitly regulated under any single IMO instrument but is increasingly referenced across discussions on greenhouse gas (GHG) reduction pathways, lifecycle emissions accounting, and future compliance mechanisms.

Within the context of the IMO Initial and Revised GHG Strategies, OCCS is viewed as a supplementary or transitional abatement option, rather than a primary zero-emission solution. The strategic focus of the IMO remains on the uptake of zero or near-zero GHG fuels and energy sources, with OCCS potentially playing a role in mitigating residual emissions, particularly for vessels operating on conventional or transitional fuels. As such, OCCS is conceptually positioned as an enabling technology rather than a standalone decarbonisation pathway.

From a regulatory standpoint, the most critical interface for OCCS lies within the development of the Global Fuel Standard / GHG Fuel Intensity (GFI) framework, which aims to regulate the average lifecycle GHG intensity of energy used onboard ships. While the IMO has indicated that zero- or near-zero (ZNZ) rewards will be allocated on a well-to-wake (WtW) basis, OCCS currently sits outside the established fuel-centric logic underpinning the GFI. As a result, the capture and removal of CO_2 onboard cannot yet be systematically reflected in GHG intensity calculations without explicit methodological expansion of the lifecycle assessment (LCA) framework.

MEPC deliberations have recognised this limitation and have acknowledged that, for OCCS to be meaningfully credited, robust, verifiable, and internationally harmonised methods for measuring captured CO_2, accounting for additional energy consumption, and confirming permanent storage or utilisation must be established. Until such methodologies are finalised, OCCS is unlikely to qualify for full recognition under future IMO compliance mechanisms, including ZNZ incentives or GFI-based compliance pathways.

In parallel, the IMO has agreed on a dedicated work plan for the development of a regulatory framework for OCCS, encompassing safety, environmental protection, and emissions accounting considerations. This work plan is expected to progress through the Marine Environment Protection Committee (MEPC) over the coming years, with indicative timelines pointing toward potential consolidation of regulatory guidance by around 2028. Until then, OCCS deployment will continue to rely on interim interpretations, pilot projects, and case-by-case approvals.

From an evaluative perspective, the current IMO position reflects a cautious but constructive approach. OCCS is acknowledged as technically feasible and potentially valuable, yet its regulatory treatment remains constrained by unresolved questions relating to lifecycle accounting, environmental integrity, and consistency with fuel-based regulatory instruments. This creates a degree of uncertainty for early adopters, particularly with respect to long-term compliance value and return on investment. Additionally, OCCS's uptake is also constrained by the absence of recognition within the short-term measure regulations EEDI, EEXI and CII.

In summary, the IMO regulatory landscape for OCCS can be characterised as recognition without full integration. While OCCS is increasingly present in strategic discussions and future regulatory planning, its formal inclusion within binding IMO mechanisms will depend on the successful resolution of accounting, verification, permanence criteria and recognition within the short-term measures. Until such clarity is achieved, OCCS remains a promising but transitional solution within the IMO's decarbonisation framework. An indicative forward timeline for how OCCS is expected to evolve within the IMO framework is assembled in Figure 60. It should be noted that this does not constitute a formally adopted regulatory roadmap, but rather an indicative trajectory derived from ongoing MEPC workstreams and related legal and policy developments.

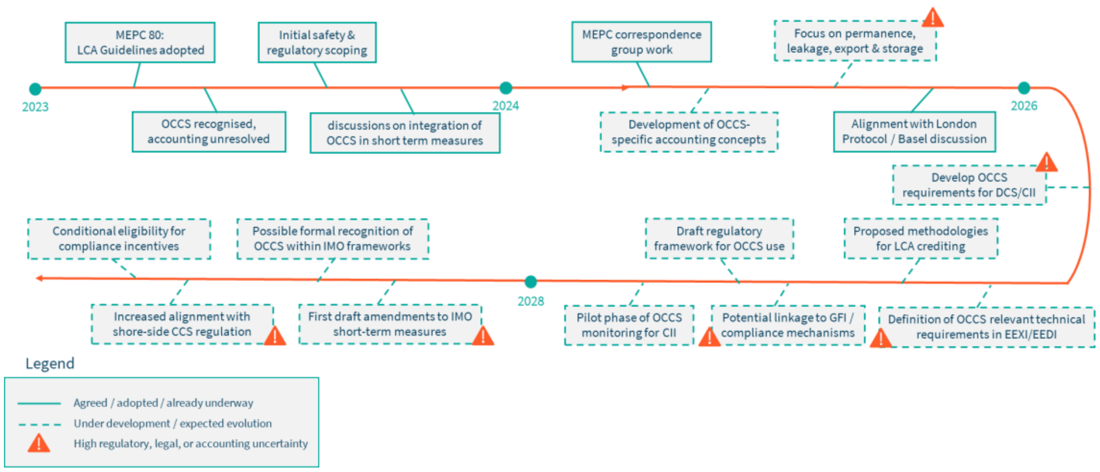


Figure 60. IMO Forward Timeline – Indicative trajectory

4.2 Regional Regulations Affecting OCCS

In parallel with ongoing developments at IMO level, regional regulatory frameworks are beginning to play a decisive role in shaping the practical viability of onboard carbon capture and storage (OCCS). In particular, the European Union has emerged as a frontrunner in establishing binding climate-related obligations for maritime transport, creating both regulatory drivers and constraints for the deployment of OCCS.

Unlike the IMO framework, which focuses primarily on global technical and operational standards, EU regulations directly impose compliance costs and incentives linked to greenhouse gas emissions. As such, they have the potential to significantly influence investment decisions related to OCCS in the near term, even in the absence of explicit international recognition of onboard carbon capture.

This section examines the EU regulatory landscape most relevant to OCCS, with a focus on the EU Emissions Trading System (EU ETS) and the FuelEU Maritime Regulation. The analysis assesses the extent to which these instruments currently recognise or could potentially accommodate OCCS and identifies key regulatory gaps that would need to be addressed for OCCS to be effectively integrated into the EU climate compliance framework.

4.2.1 EU Regulatory Landscape for OCCS – EU Emissions Trading System (EU ETS)

The extension of the EU Emissions Trading System (EU ETS) to maritime transport represents a fundamental shift in the regulatory treatment of shipping emissions within the European Union. From 2024 onwards, shipping companies are required to surrender allowances for a defined share of their verified CO_2 emissions from voyages to, from and within the EU, based on emissions reported under the EU MRV framework.

Under the current EU ETS architecture, emissions are defined as CO_2 released to the atmosphere from fuel combustion onboard ships. As such, the system is based on verified emissions rather than purely theoretical fuel consumption. While the EU MRV Regulation primarily relies on fuel-based calculation methodologies, it also explicitly allows for direct CO_2 emissions measurement, including the use of continuous emissions monitoring systems (REGULATION (EU) 2015/757, 2015). In principle, this monitoring flexibility could provide a technical pathway to account for CO_2 captured onboard, provided that the captured fraction can be robustly measured, reported, and verified in accordance with MRV requirements.

Importantly, under current EU ETS rules, ships may reduce their emissions liability where CO_2 is captured onboard and permanently stored in accordance with the EU carbon capture and storage framework. Specifically, CO_2 that is captured and transported for geological storage in a facility permitted under Directive 2009/31/EC (the CCS Directive) may be considered not emitted, subject to compliance with monitoring and verification requirements. The European Commission's Directorate-General for Climate Action (DG CLIMA) has issued guidance clarifying the treatment of onboard carbon capture under the EU ETS, including detailed rules on MRV alignment, chain-of-custody requirements, and evidence of permanent storage. However, to date, there are no well-documented practical cases of CO_2 offloaded from ships and credited under the EU ETS, meaning that implementation remains largely untested in operational terms (DG Clima, 2026).

Nevertheless, the structure of the EU ETS leaves room for further clarification and operationalisation of OCCS recognition. In principle, if captured CO_2 can be demonstrably prevented from being released to the atmosphere, transferred into a regulated carbon capture, transport, storage or utilisation (CCUS) value chain and permanent storage or permanent chemical bounding through mineralisation or solid-carbon formation is ensured, such emissions should not be subject to allowance surrender. However, this requires clear and harmonised rules on monitoring, reporting and verification (MRV), confirmation of storage certification under the CCS Directive, and robust documentation covering the entire transfer chain from ship to storage site.

At present, despite the existence of a legal basis for recognition, practical and procedural uncertainties remain for OCCS projects operating under the EU ETS. Without fully standardised implementation practices and demonstrated precedents, shipowners deploying OCCS face regulatory and administrative complexity when seeking to deduct captured emissions. Addressing these challenges will likely require further interpretative guidance, procedural harmonisation, and closer alignment between the EU ETS, MRV Regulation, and broader EU carbon management policies. To highlight the above conclusion, it is noted that LR has not witnessed any EUA crediting taking place as of February 2026, neither from an advisory nor from a verifier's standpoint.

4.2.2 Involvement of OCCS into the FuelEU Maritime Regulation

The FuelEU Maritime Regulation establishes limits on the GHG intensity of the energy used onboard ships calling at EU ports, assessed on a WtW basis. The regulation is designed to accelerate the uptake of low and zero-emission fuels by progressively tightening GHG intensity requirements over time. Under the current version of FuelEU, compliance is determined through predefined lifecycle emission factors associated with fuels supplied to the vessel. Consequently, only reductions embedded within the intrinsic carbon intensity of the fuel are recognised. OCCS is not explicitly addressed within the regulation, and there is no mechanism to treat captured CO_2 as a reduction in a ship's reported GHG intensity. As a result, any CO_2 captured after combustion does not currently improve a vessel's FuelEU compliance position.

The exclusion of OCCS at this stage reflects a combination of practical and regulatory constraints. First, the technology is still maturing, with only limited pilot-scale data available and no multi-year, commercial-scale operational evidence to support default performance assumptions for regulatory use. Second, there is no internationally harmonised chain-of-custody framework that could guarantee the traceability, custody transfer, and long-term sequestration of CO_2 captured onboard ships. Third, there is currently no verifiable monitoring, reporting, and verification methodology tailored to OCCS that would allow regulators to credibly quantify net abatement and ensure that captured CO_2 is permanently removed rather than re-emitted. These gaps collectively explain why the FuelEU methodology focuses exclusively on the carbon intensity of the fuel supplied, rather than recognising mitigation measures applied post-combustion.

Nevertheless, the Regulation contains explicit openings that could accommodate OCCS in future. Notably, FuelEU includes a dedicated Review Clause requiring the European Commission to reassess the treatment of new GHG abatement technologies, including OCC, by December 2027 (REGULATION (EU) 2023/1805, 2023). This review represents the key policy window through which OCCS could become an eligible compliance-reducing measure. The inclusion of this clause signals recognition that post-combustion abatement may become necessary as ships operating on conventional fuels face increasingly stringent GHG thresholds, particularly during the 2030–2040 period when low-carbon fuels may still be available at limited scale and high cost.

Recent EU communications reinforce this direction of travel. The Commission has explicitly stated that "CCS on board ships is an option to explore" and is examining whether temporary storage of captured CO_2 onboard could function as a compliance-reducing measure under certain conditions (CO2 Shipping & Terminals Conference, 2024). Furthermore, the EU recognises that OCCS could support pathways involving biogenic or synthetic renewable fuels by enabling closed-loop carbon cycles in which captured CO_2 is delivered to Power-to-X or industrial utilisation facilities. Although these statements do not create regulatory certainty, they demonstrate an evolving policy stance that acknowledges the potential integration of OCCS within future FuelEU compliance mechanisms.

The prospects for OCCS inclusion will depend heavily on several regulatory, technical, and infrastructural developments expected over the 2026–2030 horizon. One key requirement is the establishment of an MRV framework specifically tailored to OCCS. This would need to align with both the EU MRV Regulation and the IMO's Life Cycle Assessment Guidelines to ensure consistent accounting rules. Such a framework must define how captured CO_2 is measured onboard, how temporary storage is verified, and how custody transfer is documented upon offloading. Parallel to this, the EU will need to determine whether OCCS can be incorporated into the FuelEU methodology through delegated acts or amendments to Annexes I and IV, particularly regarding lifecycle boundaries and the treatment of post-combustion abatement.

Infrastructural progress is also essential. The European Commission acknowledges the need for the development of CO_2 transport and storage value chains to enable any regulatory integration of OCCS. This includes expansion of ship-based CO_2 transport networks by 2030, and, in the longer term, integration with EU-wide CO_2 pipeline networks expected to operationalise around 2040. Initiatives such as Important Projects of Common European Interest (IPCEI) for CO_2 transport and storage are already being advanced to create the downstream conditions necessary for large-scale OCCS deployment.

Safety and certification considerations constitute a third regulatory pillar. The European Commission has indicated its intention to "promote through the IMO the development of necessary guidelines on the safe transportation of CO_2 by sea," recognising that OCCS cannot be credibly incorporated into FuelEU until a coherent set of international safety and handling standards is established. Such standards would need to address temporary onboard storage of CO_2, transfer operations in port, and the interface with receiving terminals.

Collectively, these developments indicate that while OCCS is not currently recognised under FuelEU Maritime, the regulatory architecture is clearly evolving in a direction that could permit future inclusion, possibly towards 2030. However, OCCS remains outside the scope of recognised compliance options for the current time, underscoring the need for targeted regulatory development if onboard carbon capture is to play a substantive role in EU maritime decarbonisation.

4.2.3 EU Regulatory Framework on Offloading Captured CO_2

In addition to EU instruments directly regulating shipping emissions, a wider set of EU policies and legislative acts govern carbon capture, transport, storage and utilisation activities. These instruments were primarily developed to enable industrial CCS and carbon management onshore, but they are increasingly relevant to OCCS due to their influence on the downstream handling, transfer and permanent storage of captured CO_2. While these regulations recognise permanent CO_2 storage and support the development of carbon management value chains, they do not yet provide a clear or integrated regulatory pathway for onboard carbon capture and ship-based CO_2 offloading. As a result, OCCS currently sits at the interface between maritime regulation, port regulation and EU CCS policy, creating areas of regulatory discontinuity.

The Storage Directive (CCS Directive – Directive 2009/31/EC)

The CCS Directive establishes the legal framework for the environmentally safe geological storage of CO_2 within the European Union. Its primary objective is to ensure that CO_2 is permanently contained in geological formations in a manner that prevents adverse effects on human health and the environment.

The scope of the Directive covers the entire lifecycle of geological CO_2 storage, including site selection, characterisation, operation, monitoring, closure and post-closure obligations. It was developed in parallel with amendments to international environmental instruments, notably the London Protocol and the OSPAR Convention, in order to remove legal barriers to offshore geological storage beneath the seabed. To support implementation, the Directive is complemented by non-binding guidance documents addressing key technical and regulatory aspects, including lifecycle risk management, characterisation of storage complexes and CO_2 streams, monitoring and corrective measures, transfer of responsibility to competent authorities, and financial security requirements (DIRECTIVE 2009/31/EC, 2009).

From an OCCS perspective, the CCS Directive is significant because it provides a clear legal definition of permanent CO_2 storage. This definition underpins the conditions under which captured CO_2 may be considered effectively removed rather than emitted. However, the Directive does not address the capture of CO_2 onboard ships, nor does it regulate maritime transport or port-side temporary storage of captured CO_2. As such, while it enables the final stage of the OCCS value chain, it does not provide a complete regulatory pathway for ship-based capture and offloading.

Carbon Border Adjustment Mechanism (CBAM)

The Carbon Border Adjustment Mechanism (CBAM) is designed to address the risk of carbon leakage by placing a carbon price on certain goods imported into the EU, equivalent to the cost borne by EU producers under the EU Emissions Trading System. Its objective is to encourage cleaner industrial production globally while safeguarding the competitiveness of EU industry.

CBAM applies to imports of selected carbon-intensive goods and precursors, including cement, iron and steel, aluminium, fertilisers, electricity and hydrogen. Importers are required to declare the embedded emissions associated with these goods and surrender CBAM certificates corresponding to those emissions. The mechanism entered into force in October 2023 with a transitional reporting phase, and financial obligations will apply from January 2026 (CBAM, 2026).

In its current form, CBAM does not address emissions from maritime transport, nor does it reference carbon capture activities onboard ships operating in international waters. Indirect emissions, including those associated with transportation, remain under discussion at policy level. Consequently, CBAM has no immediate regulatory relevance for OCCS. Any future linkage would depend on whether transport-related emissions or captured CO_2 associated with logistics chains are brought within scope.

Industrial Carbon Management Strategy

The EU Industrial Carbon Management Strategy establishes a policy framework aimed at creating a single, integrated CO_2 market in Europe and accelerating investment in carbon management technologies. Its overarching goal is to support the decarbonisation of energy-intensive industries while enabling large-scale deployment of carbon capture, transport, storage and utilisation.

The strategy covers multiple technology pathways, including carbon capture and storage (CCS), carbon capture and utilisation (CCU), and carbon removals involving permanent storage of CO_2. It also identifies key enablers such as CO_2 transport infrastructure, cross-border networks, market development, and financial support mechanisms. Instruments such as the Innovation Fund, TEN-E CO_2 transport projects and coordinated research initiatives are highlighted as key tools for implementation (EC - Industrial carbon management, 2025).

Although the strategy is primarily focused on industrial emitters, its emphasis on CO_2 transport infrastructure and market creation is directly relevant to OCCS. By facilitating ship-based transport of captured CO_2 and supporting cross-border CO_2 flows, the strategy creates an enabling environment in which OCCS-related activities could be integrated, particularly where ships act as transport vectors within broader CCS value chains.

Net Zero Industry Act (NZIA)

The NZIA identifies a set of strategic net-zero technologies that are considered essential for the EU's decarbonisation pathway and suitable for large-scale industrial expansion. These include solar photovoltaic and solar thermal technologies, onshore and offshore wind energy, batteries and energy storage systems, electrolysers and fuel cells, heat pumps and geothermal technologies, grid technologies including smart grids and power electronics, and sustainable biogas and biomethane. Importantly, Carbon Capture and Storage (CCS) is explicitly included within this list, signalling formal EU recognition of its role in achieving climate neutrality alongside renewable energy and electrification solutions.

With respect to CCS, the NZIA introduces targeted measures to accelerate project development and market uptake. These measures include streamlined permitting procedures for strategic projects, improved coordination at Member State level, enhanced access to public and private financing, and support for cross-border CO_2 transport and storage infrastructure. A key quantitative objective of the Act is the establishment of at least 50 million tonnes per year of CO_2 injection capacity within the EU by 2030, reflecting the scale of carbon storage required to support industrial decarbonisation pathways. This target directly underpins the viability of future CCS value chains by addressing one of the main bottlenecks identified to date: the limited availability of permitted and operational storage sites (EC - NZIA, 2026).

From a regulatory standpoint, the NZIA does not introduce specific provisions governing ship-based carbon capture or the offloading of captured CO_2 from vessels. Nevertheless, its relevance to Onboard Carbon Capture and Storage (OCCS) is significant. By accelerating the development of CO_2 storage capacity and facilitating CO_2 transport networks, including maritime transport where relevant, the Act contributes to the creation of downstream conditions necessary for OCCS deployment. In this sense, the

NZIA supports OCCS by strengthening the wider CCS ecosystem upon which ship-based capture solutions would ultimately depend.

In terms of implementation, the NZIA reached political agreement between the European Parliament and the Council in February 2024 and formally entered into force in June 2024. Member States are expected to implement supporting measures from 2026 onwards, with the 2030 storage capacity target serving as a key milestone for evaluating progress. As the CCS market matures under this framework, further regulatory clarification may be required to address the specific role of maritime CO_2 transport and OCCS within EU decarbonisation strategies.

4.2.4 National Regulatory Frameworks Relevant to OCCS & CO_2 Offloading

Across Europe, national legislative developments and policy initiatives demonstrate a growing and increasingly coordinated commitment to Carbon Capture and Storage as a critical component of industrial decarbonisation strategies. Several European states have moved beyond high-level policy support and are actively enabling CCS through dedicated legislation, licensing frameworks, and public funding mechanisms, particularly with respect to geological storage and CO_2 transport infrastructure.

Norway

Norway represents the most advanced and operationally ready jurisdiction for ship-based carbon capture, transport and storage. Its regulatory environment explicitly permits CO_2 transport by ship, temporary handling at port facilities, and permanent offshore geological storage. This framework is already fully implemented through the Northern Lights project, which is designed to receive third-party CO_2, including volumes transported by ship from foreign emitters. Norway also provides clear rules for monitoring, verification, and long-term liability, with the state assuming responsibility after storage sites are closed and certified (Global CCS Institute, 2024). As a result, Norway stands today as the primary near-term sink for CO_2 captured onboard ships, supported by a legally mature and internationally connected CCS value chain that is unmatched elsewhere.

The United Kingdom (UK)

The United Kingdom has developed one of the world's most sophisticated offshore CCS regulatory regimes, anchored in the Energy Act and associated petroleum and storage licensing frameworks. The UK system includes defined permitting processes, explicit rules for offshore geological storage, and a structured pathway for the eventual transfer of long-term liability to the state. The UK ETS provides financial incentives for CCS deployment, recognising emission reductions only once permanent storage has been verified, thereby ensuring environmental integrity across the value chain (Global CCS Institute, 2024). UK ports are well positioned to act as aggregation and intermediate handling points for ship-captured CO_2 destined for offshore storage. The combination of regulatory clarity and strong policy incentives makes the UK a central actor in the emerging North Sea CCS ecosystem.

European Union (EU) member states

Beyond the Norway–UK core, several EU countries are progressively developing CCS frameworks that support the broader North Sea and continental European carbon management network. The Netherlands is creating large-scale CO_2 hubs, particularly in the Port of Rotterdam to enable aggregation, temporary storage, and onward transport, offering a viable collection point for ship-generated CO_2. Denmark has established an offshore storage framework with significant North Sea potential, though ship-delivered CO_2 rules remain limited. Germany is gradually shifting its historically restrictive position on CCS, with evolving legislation enabling transport and offshore storage (often outside German territory). France recognises CCS in principle within its industrial decarbonisation strategy but lacks dedicated maritime CO_2 handling rules and has limited offshore storage development (Global CCS

Institute, 2024). While these jurisdictions enable aspects of CCS, they do not yet provide complete regulatory pathways for OCCS, particularly for maritime offloading and cross-border storage.

Potential Norway–UK Synergy for an Integrated OCCS Chain

A compelling opportunity emerges from combining Norway's advanced transport and storage infrastructure with the UK's comprehensive regulatory and permitting framework. In a joint OCCS chain, Norway could serve as the primary storage and transport hub, leveraging its operational Northern Lights infrastructure, while the UK could provide robust regulatory governance, ETS-linked financial incentives, and port-side aggregation functions. Such cooperation could create the first fully functional, commercially scalable OCCS corridor, where ships capture CO_2 onboard, discharge in UK or Norwegian ports, and rely on Norway's offshore reservoirs for permanent storage. This bilateral synergy would not only accelerate early deployment but also establish a replicable model for cross-border maritime CCS logistics.

The United States of America (USA)

The United States is rapidly becoming the largest growth region for CO_2 storage capacity, driven by robust federal and state-level CCS regulatory frameworks. The U.S. already regulates capture, transport, and geological storage comprehensively, supported by expansive financial stimuli such as the enhanced 45Q tax credit and large federal investments in CCUS research, development, and demonstration. Federal permitting pathways exist for offshore sequestration (via MPRSA) and for pipelines and injection wells (via OCSLA) (Global CCS Institute, 2024). While the U.S. does not yet regulate the maritime offloading of captured CO_2, and OCCS-specific provisions are absent, there are no explicit prohibitions. The main gaps relate to third-party CO_2 importation and the absence of frameworks dedicated to ship-sourced carbon. Despite this, U.S. policy ambition and geological capacity position the country as a long-term anchor for global CO_2 storage expansion.

Theoretical Multilateral Agreement: U.S.–UK–Norway

A trilateral arrangement between the United States, United Kingdom, and Norway could form the backbone of a transatlantic CO_2 transport and storage network. Building on the earlier Norway–UK synergy, the U.S. could contribute vast additional storage capacity and long-term scalability as European reservoirs mature. The UK's regulatory structure could provide governance for verification, liability transfer, and cross-border traceability, while Norway could continue to serve as the operational storage and transport pioneer. Such an agreement would also help align national approaches with international legal constraints, especially those arising from the London Protocol's export restrictions. A coordinated multilateral framework could therefore allow ship-captured CO_2 to move between consenting parties, establish robust monitoring obligations, and create a globally integrated OCCS corridor spanning the North Sea and North America.

Asia Nations

In Asia, Japan, China, and Singapore are emerging as the region's leading jurisdictions exploring CCS and potential maritime CO_2 handling. Japan possesses a legally recognised CCS framework and is actively assessing ship-based CO_2 transport as part of its national decarbonisation strategy. China's CCS deployment is growing through successive Five-Year Plans, though it lacks a dedicated CCS law and relies on broader environmental legislation; international CO_2 transport remains unregulated but not prohibited (Global CCS Institute, 2024). Singapore, despite having no domestic storage sites and not being a party to the London Protocol, is strategically positioning itself as a future CO_2 logistics and transshipment hub, leveraging its port infrastructure and regional partnerships (Press release MTI, 2024). Potential synergies across the Asia-Pacific could link Japan's storage ambitions, Australia's vast geological reservoirs, Malaysia's emerging CCS initiatives, and Singapore's hub-and-spoke logistics model. Together, these countries could form the foundation of a regional CCS transport network, enabling ship-based cross-border CO_2 flows once international legal barriers are resolved. However, the exclusion of Singapore from the London Protocol creates significant implications to a potential bilateral agreement for the purpose of transport of captured carbon for subsea injection since a State that is not a Contracting Party to the 1996 London Protocol cannot make use of the export mechanism established by the 2009 amendment to Article 6, nor can it participate in its provisional application under Resolution LP.5(14). In practical terms, this means that Singapore (or China) cannot participate in cross-border CO_2 sequestration chains under the LP framework unless it first accedes to the Protocol.

4.3 International Environmental Conventions

In the absence of a single, CCS-specific global treaty, onboard carbon capture and storage (OCCS) must navigate a fragmented but interlinked body of international instruments that set the boundary conditions for cross-border capture, transport, storage, and potential utilisation of CO_2. Because OCCS inherently traverses multiple jurisdictions such as flag states, port states, transit states, and storage states, the applicability and interplay of conventions fundamentally shape what is legally possible, how ports may accept CO_2, what insurers will underwrite, and whether investors view projects as bankable. In practice, the London Convention and its 1996 Protocol (LC/LP) and the Basel Convention provide the clearest examples of how international law can both enable offshore geological storage and constrain the transboundary movement of captured CO_2. Where these instruments are not fully aligned or not universally implemented, OCCS deployment faces heightened uncertainty, even when technology and national laws are otherwise supportive.

4.3.1 London Convention & London Protocol

The London Convention (1972) and the London Protocol (1996) govern the dumping of wastes and other matter at sea and, since the 2006 amendment to the Protocol, explicitly allow sub-seabed geological storage of CO_2 so long as the stream consists overwhelmingly of CO_2 and is intended for permanent isolation. This dual character, permitting sub-seabed storage while controlling disposal makes LC/LP the single most consequential international framework for any OCCS value chain that contemplates offshore storage and/or ship transport to such sites.

The definition of “Dumping” in Art 4.2 of the LP excludes the disposal into the sea of wastes or other matter incidental to, or derived from the normal operations of vessels, aircraft, platforms or other man-made structures at sea and their equipment, other than wastes or other matter transported by or to vessels, aircraft, platforms or other man-made structures at sea, operating for the purpose of disposal of such matter or derived from the treatment of such wastes or other matter on such vessels, aircraft, platforms or other man-made structures.

A central constraint is Article 6 of the Protocol, which prohibits export of waste or other matter for dumping or storage at sea. For OCCS, this becomes pivotal because ship-captured CO_2 will often need to cross borders en route to offshore storage formations. In 2006, Parties amended the Protocol (RESOLUTION LP.1(1), 2006) to enable sub-seabed storage (subject to purity and permanence conditions). To address the export barrier, a further 2009 amendment to Article 6 of the London Protocol allows transboundary export of CO_2 for sub-seabed storage between consenting Parties (RESOLUTION LP.3(4), 2009). For the amendment to become legally binding, it must be accepted by two-thirds of the London Protocol’s Contracting Parties. Given that the Protocol currently has 56 Parties, this means that 37 ratifications are required. To date, only 14 States have formally accepted the amendment, leaving it well short of the threshold required for entry into force. As a temporary solution, the Parties adopted a 2019 resolution (RESOLUTION LP.5(14), 2019) allowing provisional application of the amendment, enabling countries that have ratified it to enter into bilateral agreements for cross-border CO_2 transport for storage pending its formal entry into force provided there are bilateral/multilateral agreements allocating responsibilities for permitting, monitoring, and long-term liability (WorleyParsons, 2009). As of 20 August 2025, 11 governments have deposited declarations of provisional application (Australia, Belgium, Denmark, Finland, Netherlands, Norway, Republic of Korea, Spain, Sweden, Switzerland and United Kingdom. Figure 61 shows the current state of each nation regarding the London Protocol and Convention involvement.

Figure 61. Member states of the London Convention and Protocol (Source: ResearchGate)

Implication: *Even where offshore storage is lawful, for the 56 parties to the LP exporting CO_2 by ship for purposes of sequestration can still be legally blocked unless sufficient states have ratified the 2009 amendment (i.e. resolution LP 3(4)) for it to become internationally binding or the relevant states have entered into bilateral agreements in accordance with resolution LP 5(14) .*

The application of the LC/LP regime to onboard carbon capture sits in a regulatory grey zone. The LC/LP framework was originally designed around a historical paradigm in which vessels loaded material for the purpose of disposal at sea, such as dredged spoil, sewage sludge, or industrial waste. Captured CO_2 from OCCS does not fit neatly into this model: it is generated onboard during normal transport operations, the vessel's primary purpose is carriage of goods rather than waste disposal, and the CO_2 is normally offloaded to port infrastructure for controlled subsea storage or utilisation, not dumped directly at sea. However, the LC/LP definition of "dumping" remains broad and, following the 2006 amendment, explicitly includes CO_2 streams for sub-seabed geological storage, prompting precautionary interpretations by many States that assume LC/LP applicability unless clearly excluded. At the same time, MARPOL typically governs operational discharges from ships, such as scrubber effluents or sewage-treatment by-products, raising ambiguity over whether the transfer of captured CO_2 to the seabed should be viewed as regulated dumping under LC/LP or as part of the normal operation of onboard equipment under MARPOL. If the activity is characterised as disposal of waste, LC/LP would prevail. if it is considered an operational transfer within an emissions-abatement process, MARPOL may be the more appropriate framework. Given these overlaps and uncertainties, it will be important for the IMO and the LC/LP governing bodies to clarify how the two conventions interact in the context of OCCS and to determine which instrument prevails for different types of CO_2 transfer.

In practice, LC/LP both enables (by recognising sub-seabed storage) and constrains (via export limits) OCCS. Project feasibility turns on:

- The ratification and implementation status of relevant LC/LP amendments
- The presence (or absence) of bilateral/multilateral agreements between exporting and receiving states

- How each state's domestic law transposes these international rules, including monitoring, verification, and long-term liability allocation. Where these conditions are satisfied, as in Norway–UK arrangements that contemplate cross-border storage, ship-delivered CO_2 may proceed. Where they are not, cross-border movement remains jurisdiction-dependent and potentially blocked.

Determining LC/LP Applicability to a Specific OCCS Case

For a shipowner or operator seeking clarity on whether LC/LP applies to a particular OCCS operation (e.g., offloading in State A, storage in State B, the following due-diligence sequence would be recommended:

1. Map the full chain and parties: Identify flag state, port/offloading state(s), any transit states, and the storage state (and its maritime zone). Clarify whether CO_2 will cross international boundaries before reaching a sub-seabed storage site.

2. Check LC/LP party status and amendment acceptance: For each state in the chain, confirm whether it is a Party to the Protocol, whether it has accepted/ratified the 2006 amendment (sub-seabed storage) and the 2019 (export) or earlier 2009 Article 6 export-enabling provisions referenced in the notes, and whether any state has opted for provisional application pending entry into force. This determines if export of CO_2 for sub-seabed storage is legally available. (If internal expertise is limited, consult the Convention Secretariat or the state's competent authority.)

3. Verify inter-state agreements and allocation of responsibilities: Where export is contemplated, confirm the existence (or negotiability) of the required bilateral/multilateral agreement(s) covering permitting jurisdiction, monitoring, reporting, verification, site operations, and long-term liability/transfer. Absence of these instruments is a frequent show-stopper even when storage is otherwise permitted.

4. Assess national transposition and port acceptance: Review how each involved state has transposed LC/LP into domestic law, including definitions of "waste," "dumping," and CO_2 stream specifications (purity, absence of added waste). Engage port authorities early to confirm offloading requirements, reception facility certification, and any additional environmental permits.

5. Document chain-of-custody and permanence: Prepare a traceable chain-of-custody from onboard capture through port reception, transport, and permanent storage, aligning with monitoring and liability standards expected by storage-state regulators. Where needed, seek written interpretive guidance from the IMO/LC-LP Secretariat to evidence due diligence for financiers and insurers.

6. Coordinate with parallel regimes: Consider potential interactions with other regimes (e.g., Basel, where CO_2 classification as waste vs. commodity may affect transboundary movement), to avoid conflicts that could undermine LC/LP compliance.

In practice, operators should first approach their flag-state administration and the competent authority of the offloading/storage state(s). For interpretive questions on treaty scope and amendment status, the London Convention/Protocol Secretariat (hosted at IMO) is the appropriate point of technical contact. The IMO can provide procedural clarity, however, they may typically direct case-specific determinations back to Parties' competent authorities.

4.3.2 The Basel Convention

The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal regulates the international movement of hazardous and other wastes with the aim of protecting human health and the environment. At its core, the Convention establishes a global framework governing when a material is considered a "hazardous waste," how such waste may be transported across borders, and the conditions under which it may be managed, treated, or disposed of. The Convention applies primarily to two major categories of materials: (A) hazardous wastes, as defined under Annexes I, III and relevant national determinations, and (B) other wastes, which, while not classified as hazardous, still present environmental management concerns.

Hazardous wastes, for Basel purposes, include wastes that exhibit hazardous characteristics due to their origin, composition, or inherent dangerous properties. This may encompass wastes containing heavy metals, toxic chemicals, corrosive, flammable, explosive, reactive, or infectious components, as well as certain electronic and electrical wastes and plastics when they display hazardous traits. The Convention also covers several categories of other wastes, including household waste, incinerator ashes, and selected plastic or electronic waste streams that, although not formally hazardous, require enhanced international control due to their environmental significance.

However, it is important to note that Article 1.4 of the Basel Convention explicitly states:

"Wastes which derive from the normal operations of a ship, the discharge of which is covered by another international instrument, are excluded from the scope of this Convention".

Waste emissions from a ship's operations would normally be regulated by MARPOL and therefore Basel may not apply. Of course, the subsequent transport of OCCS waste either for dumping, recycling, or reprocessing could come under the terms of Basel, but that would be conditional on a number of scenarios that yet remain uncertain.

Hence, these issues require careful consideration by the IMO Member States, and the Parties to the Basel Convention before agreeing a concrete determination of how the Basel Convention could apply. Noting that the IMO regulatory framework for OCCS is currently under development, it is important for this consideration to take place at the earliest opportunity.

4.3.3 UN High Seas Treaty (BBNJ Agreement)

The UN High Seas Treaty, formally named the Agreement under the United Nations Convention on the Law of the Sea (UNCLOS) on the Conservation and Sustainable Use of Marine Biological Diversity in Areas Beyond National Jurisdiction (BBNJ), constitutes the first globally binding regime dedicated to conserving biodiversity in the world's high seas. These areas, described legally as Areas Beyond National Jurisdiction (ABNJ), comprise approximately two-thirds of the world's ocean. For decades, activities in these waters were governed by a fragmented set of regional and sectoral rules. The Treaty therefore fills a critical regulatory gap by introducing a cooperative global framework capable of overseeing cumulative impacts on high-seas ecosystems.

The Treaty's scope is organised around four principal pillars:

- Establishment of Marine Protected Areas (MPAs) in ABNJ
- Mandatory Environmental Impact Assessments (EIAs) for activities conducted in these regions
- Access and benefit-sharing rules for Marine Genetic Resources (MGRs)
- Capacity-building and technology transfer to support equitable implementation.

Following nearly twenty years of negotiations, the Agreement was adopted on 19 June 2023, achieved the required number of ratifications on 19 September 2025, and entered into force on 17 January 2026. Its legal effect is to subject a wide range of human activities in the high seas, including scientific exploration, resource utilisation, and industrial operations, to new standards of environmental due diligence (Agreement, 2026).

The Treaty does not explicitly regulate CCS and any measures specifically intended for ships or ship equipment would need to be discussed and decided by the International Maritime Organization as the BBNJ governing body may only make recommendations where measures are within the remit of other international bodies.. However, its governance model introduces obligations that will indirectly influence any future OCCS value chain relying on CO_2 transport or offshore routing through ABNJ. The requirement for Environmental Impact Assessments applies to all activities with potential impacts on marine biodiversity, which could include the placement of subsea CO_2 pipelines, the operation of CO_2 transport vessels in sensitive regions, or any potential seabed-based CCS operations outside national jurisdiction.

Furthermore, the newly established system for High Seas Marine Protected Areas may have implications for navigational freedom, because routes that intersect protected zones could face restrictions or require rerouting. In addition, the Treaty reinforces longstanding UNCLOS obligations relating to the prevention of marine pollution, which implies that leakage risks, accidental CO_2 discharges, or operational practices associated with OCCS transport will likely fall under heightened scrutiny. In effect, while the Treaty is not a CCS regulation, it creates an expanded environmental compliance layer for any cross-boundary CO_2 routing that depends on high-seas transit or infrastructure.

4.3.4 OSPAR Convention (North-East Atlantic)

The OSPAR Convention, concluded in 1992 through the merger of the former Oslo and Paris Conventions, provides the principal regional regime for protecting the marine environment of the North-East Atlantic. Its geographic scope includes internal waters, territorial seas, Exclusive Economic Zones (EEZs), and sections of the high seas within the defined OSPAR Maritime Area (OSPAR Comission, 2025). OSPAR represents one of the world's most advanced regional marine governance frameworks and is founded on the precautionary principle, the polluter-pays principle, and the use of best available techniques and practices.

A significant development occurred in 2007, when OSPAR Parties amended the Convention to address offshore CCS directly. Through amendments to Annex II and Annex III, OSPAR formally authorised sub-seabed geological storage of CO_2, provided specific environmental and technical safeguards are met. Complementary Decisions further refined this framework. OSPAR Decision 2007/1 prohibits the storage of CO_2 in the water column or on the seabed surface, thereby excluding shallow-seabed disposal and ensuring that only deep geological formations are permissible. OSPAR Decision 2007/2 establishes conditions for safe storage, including obligations relating to risk assessments, monitoring, containment, and CO_2 stream purity.

Unlike the High Seas Treaty, OSPAR directly governs activities related to offshore CO_2 storage and therefore plays a central role in determining whether ship-captured CO_2 can be permanently sequestered within the region. OSPAR's framework only permits geological storage beneath the seabed, which aligns with the CCS model used in the North Sea, including the Northern Lights project. Operators must demonstrate long-term containment integrity, implement robust monitoring programmes, and ensure that CO_2 streams meet strict purity requirements. Any release of CO_2 into the marine environment is prohibited under OSPAR's pollution prevention mandates.

Although OSPAR does not regulate the transport of CO_2 by ship, it governs all activities from the point where the captured CO_2 is received offshore, through the injection well, and into the geological formation. As a result, OCCS deployments intending to offload CO_2 into OSPAR-regulated storage sites must ensure full compliance with the Convention's technical and environmental safeguards. In practice, the OSPAR region currently hosts the world's only long-running offshore CCS operations: Sleipner in the North Sea and Snøhvit in the Barents Sea. These projects serve as operational precedents demonstrating the feasibility of integrating ship-based CO_2 transport with offshore geological storage infrastructure, provided that such operations comply with OSPAR's requirements. The map of the area regulated by

OSPAR, as well as the location of the two active Carbon Storage facilities can be seen in Figure 62. A list of the new OCCS projects proposed to take place in the offshore area regulated by OSPAR convention can be seen in Table 11.

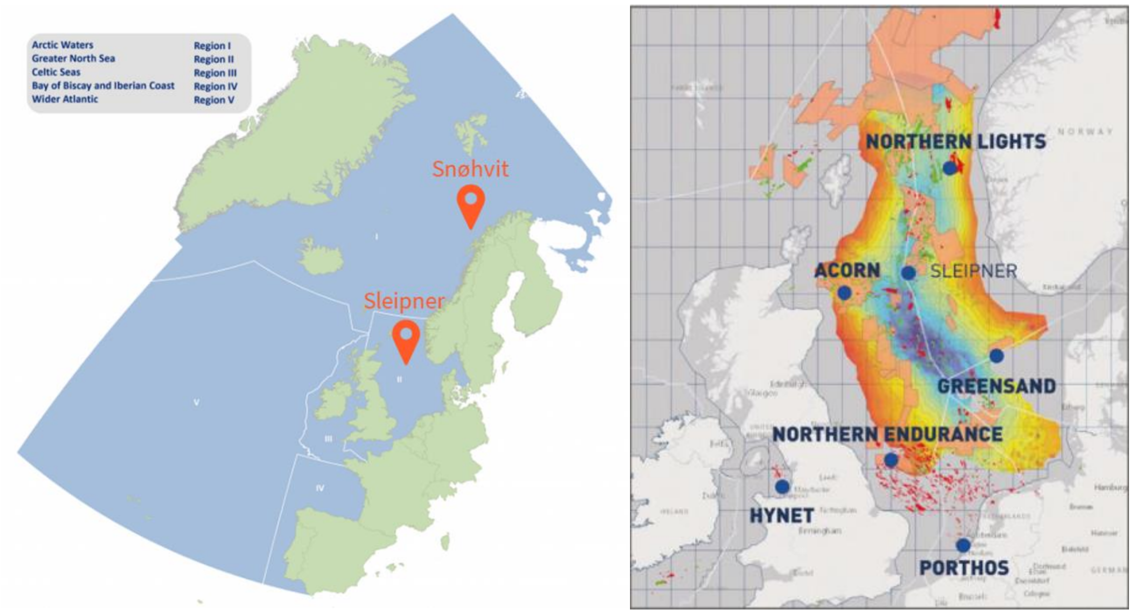


Figure 62. North Sea Area covered by OSPAR and active & proposed Carbon Storage locations (Source: UN environmental programme (left), Geo FO1 TGS (right))

Table 11. Proposed OCCS Project in OSPAR Region

Project Name	Country
Greensand	Denmark
Porthos	Netherlands
Aramis	Netherlands
Longship	Norway
Acorn	United Kingdom
Northern Endurance	United Kingdom
HyNet Northwest	United Kingdom

4.4 Classification Society Perspective

In the absence of a dedicated and fully developed global regulatory framework for Onboard Carbon Capture and Storage (OCCS), classification societies have emerged as the primary technical enablers of safe, standardised and regulatorily aligned deployment. While the IMO is progressing towards a formal regulatory structure with workstreams expected to mature post-2028, early deployment of OCCS is currently being facilitated through class rules, risk-based certification methodologies and Approval in Principle (AiP) processes.

Classification societies perform a bridging function between emerging technology and statutory acceptance. They translate conceptual OCCS technologies into structured approval pathways by developing baseline safety and design principles that ensure equivalent safety to conventional shipboard arrangements. Through formal rule development, notations and descriptive notes, class societies provide a structured framework for containment systems, pressure vessels, cryogenic handling, chemical processes, integration with propulsion systems, and crew protection. Their role spans the full project lifecycle:

- Technical Standards & Rule Development: Establishing design criteria for containment, piping, ventilation, fire protection, pressure systems and structural integration.
- Approval & Technology Qualification: Conducting design appraisals and Technology Readiness Level (TRL) assessments, issuing AiPs to de-risk early investments.
- Installation & Integration Oversight: Verifying safe integration with propulsion, exhaust systems, auxiliary power balance, stability, visibility and structural integrity.
- Operational Safety & Risk Mitigation: Applying risk-based design approaches (HAZID, HAZOP, FMEA) where prescriptive rules do not yet exist.
- Stakeholder Interface: Acting as the technical link between shipowners, shipyards, technology developers and flag Administrations.
- Future Regulatory Support: Providing the engineering and safety evidence base that will inform future IMO safety codes, GHG accounting methodologies and LCA guidelines.

As such, classification societies are currently shaping the technical architecture upon which future OCCS regulation will be built.

4.4.1 Current Class Guidance for OCCS Deployment

Class societies are actively enabling early OCCS deployment through risk-based approvals and AiP issuance, although fully harmonised prescriptive rules remain under development. Strong momentum is visible across leading societies, including DNV, LR, ClassNK, ABS and BV, all of whom are participating in IMO OCCS technical discussions and industrial pilot projects.

Cross-Society Themes

Across the major classification societies, common themes are evident:

- Dozens of AiPs have been issued globally, indicating technological readiness for pilot deployment.
- A clear understanding exists of the primary safety risks:
  - CO_2 leakage
  - Solvent handling hazards
  - Freezing and dry-ice formation
  - Tank over-pressure and venting scenarios
- Heavy reliance on risk-based design methodologies due to the absence of prescriptive IMO standards.
- Interim application of existing frameworks such as:
  - IGC Code (CO_2 storage and transfer principles)
  - SOLAS Chapter II-2 (fire and explosion safety)
  - IGF Code alternative design provisions
  - Pressure vessel rules
  - LNG and hazardous gas cargo handling principles

However, several structural gaps remain:

- No harmonised global OCCS code (IMO work ongoing, completion targeted ~2028+)
- Lack of unified global design criteria for LCO_2 tank pressure, temperature and material selection
- Incomplete integration between class approval and lifecycle accounting frameworks (LCA, EU ETS)
- Limited prescriptive safety requirements for novel solvent chemistries, refrigerants, hybrid capture technologies and emerging capture technologies such as TCD

Society-Specific Overview

ABS: Has issued the ABS Requirements for Onboard Carbon Capture and Storage Systems, first published in July 2023, establishing the classification criteria for the design, construction, installation, and survey of OCCS technologies on marine and offshore units. While centred on post-combustion, amine-based chemical absorption systems, these requirements deliberately accommodate a broader spectrum of emerging solutions—including wet scrubbing, membrane separation, cryogenic CO_2 capture, and pre-combustion removal—while also addressing integration with existing exhaust-abatement equipment such as SO_x scrubbers, SCR units, EGR systems, and Exhaust Emission Monitoring Systems. The framework sets detailed standards for onboard CO_2 storage, whether using pressurised or cryogenic tanks, requiring appropriate structural integrity, pressure-relief arrangements, leak detection, ventilation, and fire protection, and it also encompasses operational considerations such as crew safety, training, and emergency response. Recognising the diversity and varying maturity of OCCS technologies, ABS applies these rules on a case-by-case basis supported by risk assessments and offers a range of optional and mandatory class notations aligned with system readiness and verified risk-mitigation measures. While these requirements provide the primary classification pathway for shipboard carbon-capture installations, they do not override statutory obligations under SOLAS, MARPOL, or flag-state regulation, and have been developed with reference to the relevant IGC Code provisions governing CO_2 handling and storage.

BV: has issued multiple Approvals in Principle (AiPs) for a range of onboard carbon capture concepts, including membrane-assisted systems and conventional amine-based chemical absorption technologies, with each AiP assessing the feasibility of system integration, safety philosophy, containment arrangements, and alignment with SOLAS and IGC Code principles applicable to CO_2 handling and storage. While BV has not yet published a dedicated OCCS class notation, the Society incorporates OCCS-related requirements into its core machinery rules, specifically NR 467 Pt C Ch 1 Sec 12, and applies its existing frameworks on gas containment, hazardous materials, and emission-abatement systems to evaluate OCCS installations on a case-by-case basis. Beyond formal rule content, BV has issued several reports and white papers supporting industry understanding of OCCS deployment, most notably its May 2024 report Onboard Carbon Capture: An Overview of Technologies to Capture CO_2 Onboard Ships, which evaluates the technical and commercial viability of amine-based absorption, cryogenic CO_2 separation, membrane capture, and other emerging technologies, while analysing practical challenges such as energy consumption, space constraints, and the safe handling and storage of captured CO_2. BV has also published extensive guidance for liquefied CO_2 carriers, cryogenic systems, and alternative fuel integration, which indirectly support OCCS by clarifying expectations for onboard LCO_2 storage arrangements, transfer operations, and shipboard safety measures. In parallel, BV participates in several Joint Industry Projects (JIPs) aimed at strengthening CO_2 value-chain interoperability—covering topics such as onboard capture interface compatibility, CO_2 cargo quality specifications, and ship-shore transfer procedures—thus contributing to the development of harmonised standards for future OCCS uptake.

ClassNK: Has published guidelines outlining the safety requirements for systems that utilise chemical absorption with amine solutions and liquid storage of captured CO_2. Where alternative CO_2 absorption or storage technologies are proposed, these will be assessed individually in accordance with the specific design. The guidelines require a risk assessment to identify hazards that could affect personnel, the environment, structural strength, or ship integrity resulting from the installation and operation of a CO_2 capture system. When compliance with these safety requirements is confirmed, vessels may receive a corresponding class notation, which can also be applied as a readiness notation for ships preparing for future CO_2 capture capability.

DNV: DNV has developed a dedicated OCCS class notation that establishes mandatory requirements for vessels equipped with onboard carbon-capture installations, with the framework first outlined in a set of guidelines released in October 2023 and formally incorporated into the Rules for Classification in July 2024, entering into force in January 2025. These rules provide a structured, end-to-end framework for the safe design, integration, and operation of OCCS technologies on both newbuilds and retrofitted ships, targeting the principal risks associated with absorption–desorption processes and liquid CO_2 storage. The scope covers the entire OCCS lifecycle, beginning with exhaust pre-treatment—such as particulate removal, temperature control, and flow management—followed by the core capture process, which typically relies on amine-based chemical absorption but may also employ alternative technologies, including physical absorption and cryogenic separation, provided they meet equivalent safety and performance benchmarks. The requirements draw on several established regulatory and class frameworks, including rules for hazardous chemicals used in EGCS installations, main-class rules for refrigeration systems, and the principles of the IGC Code, IGF Code, and DNV's gas-carrier rules, which together provide the technical foundation for evaluating subsystem-level risks. For liquid CO_2 storage, DNV mandates tank design and approval criteria aligned with the IGC Code and its own gas-carrier rules—applicable across all vessel types in DNV class—with specific provisions addressing safe tank filling, insulation, structural integrity, pressure-relief systems, leak detection, fire protection, and the mitigation of risks such as solidification, overfilling, CO_2 toxicity, and uncontrolled releases. The rules also govern ship-shore CO_2 transfer systems, including piping, valves, automation, and emergency shutdown arrangements. Comprehensive HAZID, HAZOP, and FMEA studies are mandatory during the design phase, ensuring hazards are systematically identified and mitigated. OCCS installations must be fully integrated with shipboard machinery, automation, and safety-management systems, with operators required to implement crew training, PPE protocols, and emergency-response procedures. Compliance with broader IMO instruments, including SOLAS and MARPOL, is also required to maintain statutory alignment. DNV has indicated that the OCCS class rules will undergo further revision in 2026 as operational experience accumulates and technology continues to mature.

LR: The actions undertaken, the development of class rules, and Lloyd's Register's projected involvement in onboard OCCS and the wider value chain are presented in greater detail in sub-section 4.4.2.

IACS: has already initiated the development of a Unified Requirement (UR) for Shipboard Carbon Capture a ruleset that will establish the minimum baseline standards that equipment must meet in order to achieve Class approval. Although each classification society may continue to apply additional requirements based on its own Rules, experience, and risk-based methodologies, a system that complies with an IACS UR will, in principle, have a strong foundation for approval across all IACS member societies. The knowledge generated through collaborative initiatives such as EverLoNG (LR, BV and DNV jointly investigation technical, safety, and integration challenges) has indirectly influenced the emerging UR work by feeding shared insights, operational experience, and lessons learned into the IACS process (EverLoNG, 2025).

4.4.2 Lloyd's Register Rules & Framework for OCCS

Lloyd's Register has incorporated its OCCS requirements into Part 5, Chapter 24 of the Rules: Emissions Abatement Plant for Combustion Machinery and Other Machinery and Equipment. These include the design, construction, and installation survey requirements for EACCS (Emissions Abatement Carbon Capture and Storage) systems, as well as the criteria for issuing a READY(EACCS) descriptive note for vessels prepared for later installation of such systems. The EACCS class notation covers safety considerations related to materials, structural arrangements, containment, piping, refrigeration equipment, electrical and control systems, safety systems, vessel integration, and manufacturing. The READY(EACCS) descriptive note addresses preparatory measures such as structural provisions, layout considerations, system interfaces, material readiness, and associated electrical and safety systems to facilitate the future integration of an EACCS installation.

LR's Emissions Abatement Carbon Capture & Storage (EACCS) provides a formal class pathway for onboard capture systems. The notation provides the following format: EACCS(xx,yy) with "xx" identifying the capture technology (e.g., amine, membrane, cryogenic, mineralisation, pre-combustion/TCD) and "yy" resembling the fuel context (e.g., LNG, VLSFO etc). The READY(EACCS) notation is enabling stepwise readiness. The notation's format is READY(EACCS(xx,yy,z)) where, in addition to the previous notation, "z" represents the readiness of the OCCS technological stage:

- A– Approval in Principle granted
- S– Structural reinforcement fitted
- T– Storage tanks installed
- P– Piping & manifolds installed

Engineering assessment is undertaken through Risk-Based Certification (RBC), requiring Hazard Identification and Hazard Operability studies and demonstration of equivalent safety for containment, process equipment, ventilation/detection, and fire protection, and of robust integration with propulsion/auxiliaries (power and heat balances).

This framework also aligns LCO_2 containment and transfer elements with applicable IGC and liquefied gas design principles (materials at low temperature, fatigue and relief/venting), while providing a structure to qualify non-amine concepts as they mature (e.g., solid mineralisation, membrane hybrids).

For ships installing LCO_2 storage, LR applies the methodology of independent Type-C pressure vessels with attention to fatigue, low-temperature steel selection, insulation, and pressure-relief/boil-off management, referencing LR liquefied gas rules and the IGC Code. The IGC lists "carbon dioxide: high purity" and "carbon dioxide: reclaimed quality" as products, anchoring carriage conditions (pressure/temperature envelopes and quality), which are directly relevant to OCCS offloading/transfer specifications. Refrigeration, valves, pump rooms and venting arrangements follow LNG-derived principles adapted to CO_2's thermophysical behaviour, particularly the triple point and risk of dry-ice formation during pressure transients. LR therefore expects validated connection, purging, pressure-control and ESD procedures to prevent freezing/over-pressure events and to manage boil-off safely.

For chemicals and solvents, EACCS requires dedicated ventilation, leak detection, ESD isolation, spill containment (drip trays/drains) and PPE/emergency showers, reflecting findings from real-ship HAZIDs that documented solvent leakage, freezing risks and crew-exposure scenarios. These controls stemming from case findings are now embedded as part of class approval expectations.

In parallel, LR's reviews encompass the offloading interface: manifold design, cryogenic hose handling, interlocks and emergency release, and checks that the CO_2 quality/condition (pressure/temperature/purity) match downstream CCUS reception requirements. These elements ensure that capture at sea integrates safely with port reception, interim storage, and geologic storage or utilisation systems.

5. Conclusions & Strategic Recommendations

This section summarises the key findings of the analysis and outlines strategic recommendations to support informed decision-making going forward.

The maritime sector is under mounting pressure to decarbonise as the IMO and regional regimes tighten requirements. International shipping contributes roughly three percent of global, human-induced CO_2 emissions, and regulators have set a progressively steepening trajectory: the IMO requires a 40% improvement in carbon intensity by 2030 and targets net-zero GHG emissions from international shipping by or around 2050. In parallel, the EU has introduced well-to-wake fuel-intensity limits under FuelEU Maritime and extended the EU ETS to shipping, creating immediate compliance exposures and a clear price signal for unabated emissions.

Against this backdrop, the regulatory architecture that would allow OCCS to "count" is still incomplete and uneven across three pillars: environmental/GHG accounting, waste handling, and safety. On the GHG-accounting side, today's IMO operational indices (EEXI/EEDI/CII) offer no defined mechanism to credit captured carbon, leaving unresolved questions on how to treat the fuel-penalty of capture equipment, how to adjust design/operational formulas, and how to integrate well-to-wake (WtW) boundaries that are now being discussed in IMO's lifecycle workstreams. In the EU context, MRV and ETS frameworks are comparatively readier to recognise CO_2 that is demonstrably captured and permanently stored, yet FuelEU Maritime does not presently credit OCCS and will only be able to do so after a formal methodology is developed, with the Regulation scheduled for review by end-2027. The net effect is that the primary compliance levers still hinge on fuels rather than post-combustion abatement, and the absence of explicit OCCS accounting erodes the near-term business case even where capture is technically feasible.

Waste handling and transboundary movement add their own constraints. MARPOL lacks OCCS-specific guidance on any liquid or gaseous effluents from capture systems, the London Protocol's export solution for cross-border sub-seabed storage is not yet universally in force, and the Basel Convention can introduce friction whenever a jurisdiction classifies a captured CO_2 stream as "waste," triggering controls that complicate international routing. These asymmetries make cross-border chains viable only where bilateral arrangements and clear classifications are in place.

On the safety pillar, there is no single global code for OCCS. SOLAS does not yet prescribe capture-specific offloading procedures, crew competencies, or detection and ventilation standards tailored to CO_2 service, so early deployments rely on risk-based interpretations of existing instruments. In practice, this elevates the role of classification societies, which are publishing requirements, guidelines, and notations that address containment (including LCO_2), hazardous-chemical handling, ventilation, fire protection, monitoring, and emergency response. These class deliverables provide the most concrete, operational ruleset available today, but they are not yet harmonised and do not substitute for statutory recognition in IMO and EU instruments.

Layered on top of these regulatory realities is the broader energy-transition gap. Alternative fuels are advancing, but near-term scale is constrained by lower energy density, cost premiums, and limited bunkering availability, leaving many owners with short-term compliance obligations and few immediately deployable options. This is why OCCS is attracting attention as a pragmatic, near-term pathway. Carbon Capture has the potential to deliver meaningful tank-to-wake reductions without wholesale propulsion changes or global fuel-supply overhauls, and early pilots across multiple ship types have demonstrated substantial capture rates, marine-grade reliability, and workable integration with existing machinery. At the same time, those pilots underline what must be solved to scale: vessel-specific integration limits, assured storage pathways and reception capacity, and coherent CO_2 value chain that guarantees predictable, economically viable offloading, custody-transfer, and downstream permanent storage under a verifiable MRV regime.

Based on the regulatory analysis that was conducted through the study the following key take-aways are concluded: To unlock commercial OCCS, a regulatory framework that explicitly accounts for captured CO_2 would be critical. In absence of this, OCCS lowers stack emissions but does not provide regulatory compliance. EU ETS presently remains the only regime that can translate verified storage into a tangible incentive, while FuelEU Maritime and the IMO are moving toward lifecycle-based methodologies that could recognise OCCS after further work. Global safety rules are not yet consolidated, so class society requirements serve as the de facto baseline for safe onboard implementation. In brief, OCCS can bridge the near-term compliance gap pending full fuel transition, but it will scale only if OCCS-specific accounting, cross-border legal certainty, and harmonised safety standards. It is also highlighted that the absence of dedicated methodologies for the accounting of OCCS into IMO short terms measures (EEDI/EEXI, CII) deprived the sector of a much needed incentive for early adoption.

Across the technological landscape, post-combustion amine absorption continues to exhibit the highest technological maturity for shipboard applications. Multiple real-world pilots have demonstrated stable operation, efficient utilisation of waste heat and the ability to achieve very high CO_2 purity during liquefaction, up to 99.9 percent, thereby confirming both technical viability and strong potential for downstream utilisation or sequestration. Alternative pathways remain segment-specific but promising. Calcium looping provides an attractive solids-handling pathway for containerised or short-sea trades, while pilots such as the Seabound (AIP from LR provided), installation illustrate how mineralisation can be achieved with compact hardware and low onboard energy demand. Membrane separation and adsorption systems offer modularity and minimal chemical-handling requirements but remain sensitivity-constrained by flue-gas impurities and lack extensive maritime operational data. Thermocatalytic decomposition (TCD), particularly well aligned with LNG-fuelled vessels, offers an alternative route by preventing CO_2 formation altogether through catalytic cracking of methane into hydrogen and solid carbon, though further vessel-scale demonstrations are still required to validate complete maritime integration.

Across all demonstrations, a consistent conclusion emerges: the feasibility of OCCS integration is driven more by vessel characteristics than by the specific capture technology employed. Larger vessel classes such as LNG carriers, VLCCs and container ships provide favourable conditions; ample deck space, available waste heat, generous stability margins and electrical load headroom, which support higher-readiness initiatives. Conversely, bulk carriers and medium-range tankers face tighter spatial and thermal constraints, requiring tailored engineering approaches. Feasibility work, such as the Project REMARCCABLE for the *Stena Impero*, demonstrates that while integration is technically achievable, system installation requires careful zoning, electrical-load assessment and optimisation of thermal integration to avoid excessive parasitic energy demand.

Equally important is the choice of onboard CO_2-storage pathway, which governs endurance, operational flexibility and the practical viability of each capture method. LCO_2 storage in Type C tanks remains the most practical deep-sea option due to its high density, commercial maturity and direct compatibility with emerging port reception, despite the energy requirements associated with liquefaction. Compressed-gas storage is mechanically simple but highly volume-inefficient, limiting its suitability to small or short-sea vessels. Innovative mineralisation technologies which convert CO_2 into solid bicarbonate may offer significant advantages for shipboard applications. Unlike conventional OCCS systems that require liquefaction, onboard storage, and port-side offloading, this method produces a dissolved, benign form of carbon that could be discharged directly into the ocean during the voyage, eliminating major space, weight, and logistics barriers. The concept offers operational advantages such as continuous disposal and avoidance of cryogenic systems but faces significant challenges, particularly around regulatory approval for ocean discharge, environmental impact assessment, and long-term verification of sequestration. While the method has the potential to remove dependence on CCS infrastructure and could benefit tramp vessels without fixed routes, its deployment ultimately hinges on resolving regulatory and environmental uncertainties. Solid carbon from TCD exhibits similar handling advantages but remains niche mainly due to fuel specificity. Containerised concepts add welcome modularity and retrofit flexibility but sacrifice storage capacity, making them most suitable for early pilots and regional trades rather than high-volume deep-sea operations.

From an economic standpoint, OCCS competitiveness depends strongly on energy-price conditions, evolving carbon-intensity penalties and the cost trajectories of alternative fuels. CAPEX and OPEX figures from feasibility studies, such as the approximately $13.6 million retrofit estimate for the *Stena Impero*, illustrate the importance of waste-heat recovery, optimised liquefaction duty and operational alignment with charterers. Comparative analyses show that OCCS becomes increasingly cost-effective under rising carbon-pricing regimes, particularly where captured CO_2 can access utilisation pathways such as e-fuel synthesis or mineral-based construction materials.

Critically, the scalability of onboard carbon capture hinges on closing the captured carbon value-chain gap, not solely on the installation of capture equipment. In Northern Europe, this value chain is already beginning to solidify. The Northern Lights project in Norway has established the world's first cross-border, open-access CO_2-transport and geological-storage network, providing ship-based reception, dedicated LCO_2 terminals and certified long-term storage capacity. Complementary developments across the Netherlands, Denmark and the UK reinforce this emerging ecosystem, collectively offering the most mature and interconnected CO_2-handling landscape globally. These initiatives demonstrate that a functioning marine CO_2-value chain is technically and commercially achievable when port reception, midstream transport and regulated storage evolve in parallel.

The emergence of cross-border carbon transport and storage arrangements in Northern Europe marks one of the most significant developments in the creation of an integrated European CCUS value chain. In April 2024, five Northern European countries (Sweden, Denmark, Belgium, the Netherlands, and Norway) concluded a coordinated set of bilateral and multilateral arrangements enabling the cross-border movement of captured CO_2 for offshore geological storage. These agreements were announced during an EU informal Energy Council meeting in Brussels and collectively represent a decisive step toward a unified European CCS market centred on the North Sea, which is widely regarded as Europe's primary long-term CO_2 storage hub.

Under these arrangements, each of the four EU Member States signed an individual CO_2 transport and storage agreement with Norway, under which captured CO_2 may be shipped to the Norwegian Continental Shelf and permanently stored in dedicated geological formations. This framework directly supports the Northern Lights project, a part of Norway's Longship programme, which is designed from the outset to receive CO_2 by ship from third-party European emitters. By recognising this model of cross-border transport and offshore storage, the agreements remove long-standing regulatory obstacles linked to both national legislation and international environmental conventions. In practical terms, they establish the legal conditions required by the London Protocol for transboundary CO_2 export, including the allocation of responsibilities for permitting, monitoring, verification, and long-term liability.

Parallel to the broader multilateral arrangements, Denmark and Sweden signed a distinct bilateral agreement that further strengthens regional cooperation. This agreement establishes mutual recognition of captured CO_2 as a tradable commodity rather than a waste stream, thereby bypassing several of the legal uncertainties associated with the Basel Convention. It also aligns the two countries on monitoring, reporting and verification requirements and ensures compatibility with safety and environmental protection standards. Taken together, these provisions create a seamless pathway for captured CO_2 to move between the two jurisdictions. The transportation will be done initially by ship with the possibility of future pipeline transport once infrastructure matures.

A further milestone was reached in March 2024, when Denmark and France concluded a bilateral agreement enabling the export of French CO_2 to Danish offshore storage sites. This arrangement satisfies the London Protocol's requirements for bilateral agreements between exporting and receiving states and opens the possibility for first CO_2 exports from France as early as 2024. Initial movements will take place by ship, while longer-term plans contemplate integration with the D'Artagnan CO_2 pipeline project, which is expected to route CO_2 from France through Belgium and the Netherlands and onward to Northern storage hubs.

In effect, the 2024 agreements demonstrate that bilateral cooperation is currently the only viable mechanism for enabling international CO_2 transport and storage at scale. They illustrate how a regional CCUS market can be built even in the absence of fully operational global frameworks. These early arrangements are likely to serve as templates for future corridors within and beyond Europe, paving the way toward a globally connected CCUS value chain as regulatory, logistical, and infrastructure maturity increases. While it is true that, in principle, the eventual entry into force of the 2009 London Protocol amendment would greatly facilitate broader international CO_2 movements this outcome remains remote for the time being. The amendment requires acceptance by at least 37 of the protocol parties and currently only 14 have ratified it, leaving it far from the threshold needed for activation. In the meantime, bilateral and plurilateral agreements remain the only practical pathway for enabling cross-border CO_2 transport. In order to investigate the potential expansion of such synergies for the creation of a complete value-chain, some case studies have been conducted involving nations with active engagement in OCCS and forward looking national legal frameworks. The feasibility of each potential synergy is judged against the existing legal frameworks regulating captured CO_2 transportation and permanent storage: The London Convention/Protocol and Basel Convention.

The first case study involves a synergy between two European nations of the North Sea: Norway and the United Kingdom. Among all prospective cross-border corridors, the UK–Norway route is the most mature and legally feasible today. At the level of international ocean law, both the United Kingdom and Norway are Contracting Parties to the 1996 London Protocol and support the CO_2 export framework established through the Protocol's 2009 amendment to Article 6, which provides for the transboundary movement of CO_2 intended for sub-seabed geological storage. Although this amendment has not yet entered into force, the Parties have enabled its practical operation through Resolution LP.5(14), adopted in 2019, which allows consenting London Protocol Parties to provisionally apply the amendment pending formal entry into force. The United Kingdom and Norway have both lodged the required declarations and have concluded the necessary bilateral arrangements allocating permitting, monitoring and long-term responsibility for received CO_2. Norway's Northern Lights project has been explicitly designed to receive foreign CO_2 by ship for injection into licensed reservoirs on the Norwegian continental shelf. Collectively, these measures provide a treaty-compliant legal basis for the UK–Norway flow by operationalising the provisional-application mechanism, ensuring alignment with the Protocol's requirements and establishing clear, durable responsibility frameworks for transboundary CO_2 transport and permanent storage.

From the perspective of transboundary waste law, the Basel Convention does not, per se, obstruct this corridor. Where captured CO_2 is destined for permanent geological storage and treated within the receiving country's CCS regime, it is generally managed as a regulated CCS stream rather than as a hazardous waste. Even in the more conservative case where a shipment is treated as a Basel "waste", the UK to Norway movement is an OECD-to-OECD flow, for which the Convention's Prior Informed Consent (PIC) procedure provides a workable licensing route. The Basel Ban Amendment, which prohibits exports of hazardous waste from OECD/EU Parties to non-OECD countries, does not apply. Therefore, with PIC and environmentally sound management assured, Basel does not prevent the UK-Norway project.

The above case study is enriched by the inclusion of the US in the parties involved. The US, being a nation with vast CO_2 storage capacity, could play a significant role in the creation of such a value chain. However, the EU to US export would drastically increase the legal complexity of the project. While Norway can lawfully export captured CO_2 under the Protocol's export pathway, the United States is not a Contracting Party to the 1996 London Protocol, not having accepted the Article 6 export amendment nor its 2019 provisional-application mechanism. As a result, an onward shipment from Norway to the United States for offshore geological storage would not be covered by the London Protocol's export solution and, in effect, remains blocked at the Protocol level unless and until the United States becomes a Party and accepts the amendment (or an alternative legal route consistent with the instruments is established).

From the perspective of transboundary waste law, the Basel Convention does not prohibit an EU nation from exporting to US. Where CO_2 is handled as a regulated CCS stream destined for permanent geological storage, States frequently treat it as a dedicated CCS material rather than a hazardous waste. Even under a conservative assumption, where the product was treated as hazardous waste under Basel, the movement would be OECD-to-OECD. In such a case, the shipment could, in principle, proceed under Prior Informed Consent, provided environmentally sound management is demonstrated. the Basel "Ban Amendment" would not be triggered and practically Basel restriction would remain manageable.

This case study shows that the UK–Norway corridor is emerging as the global benchmark for cross-border CCS, pairing credible legal frameworks with operational storage capacity in the North Sea. By contrast, the United States, while a world leader in subsurface storage potential, remains legally insulated offshore in the European context, limiting near-term transatlantic flows. As a result, early OCCS value chains will coalesce around North Sea–centric hubs, deepen EU/EEA cooperation, and prioritise short-sea CO_2 shipping routes that can be scaled quickly while broader international alignment catches up.

A similar strategic role is emerging in the wider APAC region, where several major maritime hubs located along the principal east–west shipping corridors are positioning themselves to become cross-border CO_2 aggregation centres. Governments and industry coalitions across the region are developing regulatory frameworks, initiating bilateral agreements, and advancing early studies for CO_2 import, conditioning and permanent storage, signalling the formation of a future regional value chain. These early efforts, including cross-border CCS agreements between regional states, the appointment of lead developers for multi-national CO_2-management initiatives and the exploration of ship-based CO_2 aggregation pathways, indicate that APAC's role in the global CO_2 transport network will expand significantly as geological storage capacity in countries such as Indonesia, Malaysia and Australia becomes accessible. Crucially, the emergence of such APAC hubs ensures that onboard capture is not confined to scheduled liner services alone. Tramp vessels, which represent roughly half of the global fleet and operate without fixed trading patterns, could periodically route through these regional hubs to offload captured CO_2, much as they would in established European centres such as Rotterdam or Antwerp-Bruges.

Furthermore, the existence of these hubs reduces the integration barriers for tramp shipping by enabling flexible offloading strategies. When direct port discharge is unavailable, vessels can offload captured CO_2 via ship-to-ship transfer to dedicated LCO_2 carriers. This dual-pathway model, direct hub offloading or mid-sea STS to a receiving carrier, means tramp operators are not structurally excluded from adopting OCCS, even in the absence of infrastructure at intermediate ports. Instead, they can participate in developing green-corridor-like carbon-handling networks by aligning their voyages with established offloading nodes in deep-sea trades or by leveraging shuttle-carrier services in regions where terminal readiness is still developing.

Another case study is conducted, between Asia Pacific nations with noteworthy OCCS capacities and the possibility of the near-future creation of a local OCCS hub is explored. A viable Asia-Pacific analogue to the North Sea model would link capture in Japan and South Korea (industrial facilities and, where relevant, shipboard OCCS) with liquefaction and short-sea shipping by regional CO_2 carriers to offshore geological storage in Australian waters. An optional design feature is a shared CO_2 reception hub in Northern Australia (aggregation, interim storage, ship-to-ship or ship-to-shore transfer) prior to injection. This mirrors the core features of Norway's Northern Lights concept transposed to the Asia-Pacific basin.

From the standpoint of international ocean law, the London Protocol provides the decisive framework. The 2006 LP CO_2 amendment allows sub-seabed geological storage of qualified CO_2 streams when purity and waste-exclusion criteria are met. Japan, the Republic of Korea, and Australia are Parties to the

London Protocol, which is legally favourable. Exports from Japan or Korea to Australia are permitted provided bilateral or trilateral agreements under Article 6 are concluded, Annex 1 purity conditions are satisfied, and storage occurs in sub-seabed geological formations licensed by the receiving State. There is therefore no structural LP barrier for this configuration, assuming Parties use the 2019 provisional-application route while the 2009 amendment awaits formal entry into force.

The Basel Convention requires a separate legal check only if the transboundary CO_2 stream is treated as a waste. Many jurisdictions handling CCS treat captured CO_2 for permanent geological storage as a regulated CCS stream rather than a hazardous waste, but classification can vary by national law. If, conservatively, CO_2 were deemed a Basel waste, cross-border movement from Japan/Korea to Australia would be OECD→OECD. In that case, Basel's Prior Informed Consent (PIC) procedure can authorise the shipment, and the Basel "Ban Amendment would not be triggered. In short, Basel risk is moderate but manageable for this tri-national corridor. A Japan–Korea–Australia regional hub is legally cleaner than many inter-regional scenarios because all three States are LP Parties, can rely on provisional application for CO_2 export under Article 6, and can navigate Basel within an OECD–OECD context and could potentially replicate the Norway–EU model in the Asia-Pacific basin and scale through short-sea CO_2 shipping to Australian storage sites.

The next step would be including China to this potential Asian OCCS hub. This creates a structural legal asymmetry under global ocean-dumping law. Unlike the rest of the nations, China participates under the 1972 London Convention but is not a Party to the Protocol. Thus, if China were to export captured CO_2 to Australia for injection offshore, the receiving State's obligations would arise under the LP framework, while China's obligations would be anchored in the LC, creating regime asymmetry and legal uncertainty over how to implement the LP's Article 6 allocation of responsibilities. In practical terms, adding China introduces a break-point that cannot be solved by the 2019 LP provisional application.

Under the Basel Convention, the introduction of China significantly heightens regulatory complexity. Because China is not an OECD country, any CO_2 stream that a Party classifies as a hazardous waste would trigger the Basel Ban Amendment. While a CCS-grade CO_2 stream may be treated as a non-waste in some national systems, China's more precautionary stance toward transboundary waste movements increases the likelihood of stricter interpretation and therefore greater compliance risk. Even in cases where CO_2 is not classified as hazardous, administrative procedures would still be more demanding due to China's conservative regulatory approach. Overall, the Basel layer introduces a material constraint for China-inclusive flows and adds another point of asymmetry atop the London Convention/Protocol divide. This scenario shows how impactful the classification of the captured product could be proven. OCCS systems that offer a final product of high purity in CO_2 can provide a significant commercial benefit to the owners since pure CO_2 products have a higher chance to be classified as products or commodities instead of "waste".

Outside Northern Europe, reception capacity remains limited and fragmented. Standardisation of CO_2 purity specifications, conditioning requirements, pressure–temperature envelopes and custody-transfer documentation is urgently needed to support interoperable systems across regions. Policy alignment, long-term contracting frameworks and harmonised rules of carriage will be essential to unlock investment in receiving terminals, liquefaction hubs and regional storage networks.

Within this context, strategic deployment of OCCS requires a structured, data-driven approach. Decisions regarding timing, scope and system configuration should be anchored in vessel-specific integration conditions, route-based offloading accessibility and long-term cost competitiveness. A route- and vessel-specific strategy is essential: LNG carriers, boxships and large tankers offer favourable thermal and spatial conditions that support high capture rates; vessels in dense liner trades may benefit from mineralisation-based solutions that leverage container-logistics; and heat-limited or space-constrained segments require careful balancing of capture targets with endurance and storage limits. For the tramp sector, regulatory frameworks should recognize multiple storage and offloading pathways as valid compliance options and establish clear, standardised protocols for measurement, reporting, and verification of captured CO_2, ensuring feasibility across vessels with irregular routes and diverse operational conditions.

Finally, organisations should regard OCCS as a strategic capability that enhances both current compliance and future optionality. Although short-term regulatory uncertainty persists, particularly following the IMO's decision to postpone adoption of the Net-Zero Framework and associated GHG Fuel Standard (GFI), the overall trajectory of maritime decarbonisation remains unchanged. Early engagement, disciplined piloting and coordinated value-chain development will position shipping companies to respond effectively once policy momentum accelerates and carbon-price signals strengthen. OCCS is therefore best understood not as a stand-alone retrofit decision but as a phased, strategic investment that prepares the fleet for a regulatory and commercial landscape where carbon abatement is both expected and economically consequential.

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Appendix A - Technology Readiness Levels (TRL) and Commercial Readiness Levels (CRL)

The technology readiness level indicates the maturity of a solution within the research spectrum from the conceptual stage to being marine application-ready. It is based on the established model used by NASA and other government agencies and institutes, using a 9-level scale.

Technology readiness level (TRL)		Description
1	Basic principles observed and reported	Scientific research begins to be translated into applied research and development. Examples include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively low fidelity compared with the eventual system. Examples include integration of ad hoc hardware in the laboratory.
5	Component and/or breadboard validation in relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include high fidelity laboratory integration of components.
6	System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond that of TRL 5, is tested in its relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.
7	System prototype demonstration in an operational environment	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requirement demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, a vehicle, or space).
8	Actual system completed and qualified through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9	Actual system proven through successful mission operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

Figure 63. Technology Readiness Levels (U.S. Government Accountability Office, 2020)

The Commercialisation Readiness Level (CRL) is a measure of how prepared a technology or product is for commercial deployment and market entry. While similar to the Technology Readiness Level (TRL), the CRL focuses specifically on commercial viability rather than technical maturity.

CRL	Description
1	Knowledge of applications, use-cases, & market constraints is limited and incidental, or has yet to be obtained at all.
2	A cursory familiarity with potential applications, markets, and existing competitive technologies/products exists. Market research is derived primarily from secondary sources. Product ideas based on the new technology may exist, but are speculative and unvalidated.
3	A more developed understanding of potential applications, technology use-cases, market requirements/constraints, and a familiarity with competitive technologies and products allows for initial consideration of the technology as product. One or more "strawman" product hypotheses are created, and may be iteratively refined based on data from further technology and market analysis. Commercialization analysis incorporates a stronger dependence on primary research and considers not only current market realities but also expected future requirements.
4	A primary product hypothesis is identified and refined through additional technology-product-market analysis and discussions with potential customers and/or users. Mapping technology/product attributes against market needs highlights a clear value proposition. A basic cost-performance model is created to support the value proposition and provide initial insight into design trade-offs. Basic competitive analysis is carried out to illustrate unique features and advantages of technology. Potential suppliers, partners, and customers are identified and mapped in an initial value-chain analysis. Any certification or regulatory requirements for product or process are identified.
5	A deep understanding of the target application and market is achieved, and the product is defined. A comprehensive cost-performance model is created to further validate the value proposition and provide a detailed understanding of product design trade-offs. Relationships are established with potential suppliers, partners, and customers, all of whom are now engaged in providing input on market requirements and product definition. A comprehensive competitive analysis is carried out. A basic financial model is built with initial projections for near- and long-term sales, costs, revenue, margins, etc.
6	Market/customer needs and how those translate to product needs are defined and documented (e.g. in market and product requirements documents). Product design optimization is carried out considering detailed market and product requirements, cost/performance trade-offs, manufacturing trade-offs, etc. Partnerships are formed with key stakeholders across the value chain (e.g. suppliers, partners, customers). All certification and regulatory requirements for the product are well understood and appropriate steps for compliance are underway. Financial models continue to be refined.
7	Product design is complete. Supply and customer agreements are in place, and all stakeholders are engaged in product/process qualifications. All necessary certifications and/or regulatory compliance for product and production operations are accommodated. Comprehensive financial models and projections have been built and validated for early stage and late stage production.
8	Customer qualifications are complete, and initial products are manufactured and sold. Commercialization readiness continues to mature to support larger scale production and sales. Assumptions are continually and iteratively validated to accommodate market dynamics.
9	Widespread deployment is achieved.

Figure 64. Commercial Readiness Levels (US Advanced Research Projects Agency)

Appendix B – Selected Q & A section

1) What is the ranking of the OCCS technologies in terms of:

    - Technology readiness;
    - Fuel consumption;
    - Capital cost;
    - Operational cost;
    - Safety;
    - Environmental performance.

    Please refer to section 2.9 Comparative Assessment of OCCS technologies, Table 6. CCS Technology rankings.

2) What are the ship types or ship sectors whose needs most closely align with each OCCS technology?

    Please refer to Table 7. Operational Suitability of Carbon Capture Technologies in Liner and Tramp Shipping as well as the commentary section 3.6 Implications for Liner and Tramp Shipping in the CO_2 Value Chain.

3) What is the status of development of the IMO OCCS regulations, and what is the process and schedule for completing these?

    An overview of the development status of IMO regulations related to OCCS can be seen through section and table through section 4.1. Subsections 4.1.1-3 address the status of emission regulations towards the accounting of OCCS while subsection 4.1.4 examines the development status of IMO safety regulations. An indicative forward looking plan from the development of those regulations is described in subsection 4.1.5.

4) What existing regulatory incentives are there for OCCS, and what are the prospects for further incentives, e.g. within the IMO GHG regulations and the European Union's FuelEU Maritime?

    At the current stage, regulatory financial incentives for the adoption of OCCS are provided solely under the EU ETS regulation (please view subsection 4.2.1). Future incentives may be available under FuelEU Maritime Framework (please view subsection 4.2.2), the CII regulation (please view subsection 4.1.3), the IMO GFI through the LCA guidelines (please view subsection 4.1.1 & 4.1.2) and future IMO market-based measures.

5) What other international, regional, and national regulations have relevance to OCCS and what is the impact of these; e.g. on transboundary movement of waste carbon, and/or sequestration?

    Please refer to subsections 4.2.3, 4.2.4 and section 4.3 for more details on the existing global and regional regulatory framework with the potential to impact the OCCS Value-Chain.

6) What relevant class rules and standards exist, and how are these currently being used?

    Please refer to section 4.4 for an overview of the existing class rules and methodologies for the assessment of OCCS.

7) Which ports have, or plan to have CO_2 reception facilities and what limitations are being imposed by the port, e.g. in terms of purity, quantity, pressure, temperature, flow rate etc. Also, what means of disposal or use is the port offering, e.g. sequestration, production of alternative fuels etc.?

   Please refer to section 3.5.3Summary of Ports with CO_2 Reception Capabilities, Technical Requirements and Disposal PathwaysPort Infrastructure

8) What OCCS pilot projects have gone ahead, and what is their status?

   Please refer to section 2.8

9) What are the barriers to uptake of OCCS, and how can these be overcome?

   The barriers for the uptake of OCCS can be split into 3 main categories: technical and operational barriers, disposal of the CO_2 and other byproducts and lastly regulatory barriers.

   The technical and operational barriers towards the adoption of OCCS can be found in section 2.6

   For the barriers linked to the disposal of CO_2 please refer to sections 3.2.4, 3.3.5 and 3.4.5

   The most significant regulatory barriers for the creation of an advanced OCCS Value-Chain are described in subsections 4.3.1 and 4.3.2 while safety related concerns are described in subsection 4.1.4.

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