MARITIME TECHNOLOGIES FORUM

LEADING THE MARITIME WORLD FORWARD

SAFE ONBOARD CARBON CAPTURE AND STORAGE

Abbreviations and Definitions

Abbreviation	Definition
CCC	Carriage of Cargoes and Containers, IMO Subcommittee
CII	Carbon Intensity Indicator
DCS	Data Collection System
EEA	Exhaust Emission Abatement
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EGCS	Exhaust Gas Cleaning System
ETS	Emissions Trading System
EU	European Union
GHG	Greenhouse Gas
HTW	Human Element, Training and Watchkeeping, IMO Subcommittee
IACS	International Association of Classification Societies
IGC	International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IMO	International Maritime Organization
ISWG-GHG	Intersessional Working Group on Reduction of GHG Emissions from Ships
LCA	Life Cycle Assessment
LCO_2	Liquefied CO_2
MEPC	Marine Environment Protection Committee
MRV	Monitoring, reporting and verification (mechanisms)
MSC	Maritime Safety Committee
MTF	Maritime Technologies Forum
OCCS	Onboard Carbon Capture and Storage
SOLAS	International Convention for the Safety of Life at Sea

Disclaimer

The findings and recommendations in this report represent a collaborative effort between participating MTF members. Each organization within the forum may have an independent opinion different from the results presented in this report. This report does not stop MTF members from having independent opinions or conclusions.

This report presents MTF's independent analysis and should not be interpreted as an endorsement by MTF of OCCS's actual effectiveness in reducing GHG emissions for ships, as this has yet to be verified and the accounting and treatment of the captured carbon will need to be taken in totality.

Executive Summary

The Maritime Technologies Forum (MTF) is a group of flag States and classification societies which aims to bridge the gap between technological progress and regulatory process. For this report, MTF carried out a high-level analysis of current regulations and ongoing discussions to identify key drivers for safe adoption of onboard carbon capture and storage (OCCS).

The '2023 IMO Strategy on Reduction of GHG Emissions from Ships' outlines the IMO's goals for reducing carbon emissions to net zero (or near) by 2050. To achieve this, alternative fuels will likely need supplementary carbon emission reduction measures, such as onboard carbon capture. Onboard carbon capture and storage (OCCS) has the potential to contribute to maritime decarbonization efforts in shipping and is a topic for the industry to explore further, with a focus on its safety, cost effectiveness and a trusted downstream MRV framework to ensure GHG emission reduction.

Taking a broader perspective, the downstream value chain, attribution of responsibilities and system cost-effectiveness are key considerations. A secured downstream value chain is the most important pre-requisite for OCCS implementation. Societal acceptance for OCCS is only expected when captured CO_2 can be securely transferred into long-term permanent storage, assured by a trusted MRV system. OCCS system cost-effectiveness is also essential for the widespread adoption of OCCS, as the technology requires significant amounts of additional energy to operate as well as capital to install. With the significant heat and power demands of operating an OCCS, a substantial increase in fuel consumption can be expected with the current technologies. Thus, to assess the net CO_2 capture rate of an OCCS, it is essential to consider emissions resulting from the additional heat and power demand of the system in operation plus associated emissions related to transport and their storage, i.e., assess the OCCS using a lifecycle analysis. While this report acknowledges the critical importance of a secure downstream value chain and cost-effectiveness for this technology to succeed, it only covers the regulatory and safety considerations of the onboard technology.

The safety challenges of OCCS depend on factors such as the complexity of the capturing technology, its location on the vessel, the type of vessel where it is installed, the designed operating conditions, and the harsh marine environment. Classification rules and guidelines have addressed some of the key challenges, but there are areas that are not fully covered and require further evaluation, such as carbon dioxide impurities and toxicity, covering other OCCS technologies other than chemical absorption, as well as safety management and crew training.

The regulatory framework for onboard carbon capture is evolving due to recent advancements in safety and environmental performance regulations. The Maritime Safety Committee (MSC) has been discussing this topic and has decided to create a roadmap before determining which sub-committees should be involved in developing new regulations. Additionally, the Marine Environment Protection Committee (MEPC) has formed a new correspondence group regarding the development of a regulatory framework for OCCS. At present, OCCS is not covered in EU regulations (EU ETS and FuelEU Maritime) but updates to account for OCCS are discussed and can be expected to be incorporated at a later time.

Overall, a successful implementation of OCCS requires a collaborative effort among all stakeholders, driven by a shared commitment to decarbonize the maritime industry. By addressing the technological, economic, regulatory, and downstream value chain challenges outlined in the report, the shipping industry might work towards implementing OCCS to reduce GHG emissions on a lifecycle basis.

This report proposes several key next steps to facilitate the adoption of OCCS in the maritime industry. The full list of recommendations tailored to relevant stakeholders can be found in the main part of this report:

1. Collaborate to create a secured downstream value chain comprising of CO_2 offloading facilities, transport infrastructure and long-term storage, together with associated MRV schemes, aiming that captured CO_2 is permanently stored.
2. Establish clear and consistent regulations on safety and environmental performance, which include:
   a. Develop safety guidelines specifically for OCCS, covering aspects like equipment design, risk assessment, and emergency response procedures.
   b. Consistently incorporate OCCS into existing regulations, such as the EEDI, EEXI and CII as well as into the EU ETS and FuelEU Maritime.
   c. Develop certification schemes for downstream CO_2 value chain infrastructure.
3. Define acceptable levels of CO_2 impurities and develop standardized guidelines for safe CO_2 handling, including offloading procedures and port infrastructure requirements.
4. Amend the Safety Management Systems and develop specialized training programs for crew members covering the operation, maintenance and emergency procedures for OCCS systems.
5. Focus on development of OCCS technologies to increase CO_2 capture rates, reduce energy demand and, thus, increase cost-effectiveness and demonstrate OCCS systems in pilot projects to gather operational experience.

Introduction

The Maritime Technologies Forum (MTF) is a group of flag States and classification societies which aims to bridge the gap between technological progress and regulatory process. This report provides recommendations to industry stakeholders for developing and implementing safe onboard carbon capture and storage (OCCS). This report aligns with the Forum's mission to explore potentially sustainable and environmentally friendly technologies in the maritime sector for achieving safe decarbonization. By collaborating on this report, MTF members utilized their combined expertise to offer guidance to the shipping industry, facilitating the safe implementation of this technology. Furthermore, the insights gained from this work aim to contribute to the development of international regulations and encourage the adoption of innovative solutions such as OCCS. The recently published report on 'Updated fuels evaluation through MTF framework [1], touches on the viability of MGO + CCUS as an option for reducing GHGs. It ranks highly on technology and potential for regulatory maturity, while offering moderate GHG emission intensity reductions.

Onboard carbon capture and storage (OCCS) has the potential to contribute to decarbonization efforts in shipping and should, therefore, be a topic for the industry to explore. Onboard carbon capture works by extracting carbon dioxide directly from a ship's exhaust gases. The captured CO_2 is then stored onboard in a compressed or liquefied form for offloading and later in secure permanent storage or utilized.

In July 2023, the International Maritime Organization (IMO) adopted a revised GHG strategy with a strengthened ambition for international shipping to reach net-zero GHG emissions by or around 2050, with indicative checkpoints of 20% reduction, striving for 30% by 2030 and 70% reduction, striving for 80% by 2040, compared to 2008 levels. The revised strategy sets ambitious targets for the marine sector, including a target to achieve an uptake of zero or near-zero GHG emissions technologies, fuels and/or energy sources, representing at least 5%, striving for 10% of the energy used by international shipping by 2030.

The deployment of OCCS technology onboard ships is one interim pathway for international shipping to move towards the strengthened IMO ambitions. Looking ahead, vessels powered by conventional fuels will continue to operate for the next few decades and utilization of OCCS technologies could provide a route to manage emissions prior to zero-carbon emission fuels becoming viable and widely used alternatives. A recent study exploring onboard carbon capture on ships found that the technology is feasible for the maritime industry, however, it requires considerable vessel modifications and increases fuel consumption [2].

IMO has acknowledged the potential of onboard CO_2 capture technologies in mitigating maritime GHG emissions. To understand this technology, the IMO has initiated the discussion on developing a regulatory framework [3]. The discussion is currently taking place within a correspondence group and the work of the correspondence group will be reported to the IMO's Marine Environment Protection Committee (MEPC) at MEPC 83 in Spring 2025. From the perspective of the European Union, a comprehensive regulatory framework has been established to reduce emissions from the shipping sector. This includes maritime emissions covered by EU ETS and the FuelEU Maritime Regulation.

At present, OCCS is not accounted for in the FuelEU Regulation. It is only in the event of future technological progress concerning new GHG abatement technologies, such as onboard carbon capture, that the Commission might assess the possibility of proposing some changes, if appropriate. For instance, those might be reflected in the GHG intensity and compliance balance formulas set out in Annexes I and IV of Regulation (EU) 2023/1805. The contribution of such technologies to lowering the GHG direct emissions on board ships is subject to the availability of a verifiable method for monitoring, accounting for permanent storage of the captured carbon [4].

The rules on carbon capture and storage (CCS) and carbon capture and utilization (CCU) under the EU ETS are currently being updated, so only preliminary guidance is available [4]. Ships that capture part of their CO_2 emissions, ensuring the CO_2 is not released into the atmosphere or environment, can account for this reduction in their GHG emissions for EU ETS purposes. However,

the total emissions before capture must still be reported under the MRV Maritime Regulation. The captured CO_2 must be geologically stored in a compliant storage site to be eligible for emission deductions. The relevant parameter for calculation is the amount of CO_2 handed over to a transport system operator or storage site, not just the amount captured. Additionally, the EU ETS Directive allows for "permanent CCU" as a reason for deducting CO_2 from emissions, with more detailed rules forthcoming. CO_2 capture is energy-intensive, and any additional emissions from this process must be included in the ship's monitoring plan. If a ship transports CO_2 as cargo, emissions from leakage or boil-off fall under the normal EU ETS rules for CO_2 transport and are not included in the MRV Maritime Regulation monitoring plan [5].

By 2027, the EU is expected to formalize its stance on OCCS, as the region continues to advance its climate goals under the "fit for 55" package, which aims to cut net GHG emissions by at least 55% by 2030 [6]. The potential inclusion of OCCS in emissions compliance calculations could provide a critical pathway for vessels to meet the increasingly stringent carbon reduction targets set by both the EU and IMO.

In the upcoming chapters, we will discuss the necessary steps for implementing OCCS technology in the maritime industry. We will highlight the importance of a secure downstream value chain and system cost-effectiveness, although this report does not cover both pre-requisites explicitly. The report will also address safety challenges associated with OCCS, including design challenges such as space and weight constraints, and compatibility with ship systems. Since international regulations have not yet addressed these challenges, we will explore how Classification rules and requirements can help ensure safe implementation onboard the ship. Additionally, the report will offer a set of recommendations to establish a strong framework for OCCS systems, tailored to relevant stakeholders.

Prerequisites For an Assured Value Chain and Commercial Adoption

The successful implementation of OCCS in the maritime industry relies on two essential prerequisites from the economic and operational perspectives: cost-effectiveness and a secured downstream value chain. These factors are essential for attracting investment, ensuring operational feasibility, and maximizing the environmental benefits of the technology as the captured CO_2 needs to be securely stored/utilized effectively.

A secured downstream value chain is the most important prerequisite for OCCS implementation. This contains the infrastructure and processes for offloading, transporting, and permanently storing (or utilizing) the captured CO_2. A fragmented approach with insufficient infrastructure and unclear responsibilities among stakeholders poses a barrier to adoption and societal acceptance. Establishing a robust downstream value chain potently requires:

Development of offloading infrastructure: investment is required in dedicated terminals or receiving vessels equipped to safely and efficiently offload liquefied CO_2 from ships.

Integration with CCUS infrastructure: Integrating the captured CO_2 from ships into existing or planned carbon transportation and storage networks to ensure the permanent sequestration of captured CO_2.

Standardization of CO_2 quality: Establishing clear specifications for the purity and composition of captured CO_2 is crucial for ensuring compatibility with different transportation, storage, and utilization options.

Accepted certification: a robust certification scheme for quantifying, monitoring, and verifying carbon removal needs to be in place to ensure value chain elements for accepting proposed CO_2 transportation and storage as solutions.

Cost-effectiveness is crucial for the widespread adoption of OCCS. The technology requires significant capital expenditure for the installation of capture units, CO_2 conditioning systems, and storage tanks. Operating costs are also a major consideration, including additional energy consumption for capture, CO_2 compression and liquefaction, and potential fuel penalties. There is a need to minimize both capital and operating costs to enhance the economic viability of OCCS. These can potentially be achieved through various means:

Technological advancements: Research and development of more efficient capturing technologies and systems that can reduce energy consumption and operating cost.

Optimization of system design: Minimizing the size of process equipment and storage tanks to reduce both capital costs and the impact on space.

Economies of scale: As the OCCS market matures and standardization increases, production costs are expected to decrease.

Policy incentives: Government support through subsidies, funds, or carbon pricing mechanisms can help offset the initial investment costs and make OCCS more attractive to shipowners.

Safety Challenges with OCCS

The safety challenges of OCCS would depend on a number of factors like the complexity of the capturing technology, its location on the vessel, type of vessel where it is installed, the designed operating conditions and the harsh marine environment. Below are some of the key challenges.

Design Challenges

1. **Space and weight constraints:** Space onboard vessels is limited as the intent is to carry as much cargo as possible. More machinery and additional weight mean less amounts of cargo that the vessel can carry. Moreover, retrofitting an OCCS on existing vessels is more challenging as the OCCS and sub-systems need to be designed to fit in the available space (in some cases outside of hazardous areas), and it must be ensured that the power and auxiliaries available onboard are sufficient to support the proper operation of the OCCS system. Proper design is to take into consideration the space required for maintenance as well.
2. **Compatibility with ship's systems:** For retrofits, integrating OCCS with the ship's systems can be complex. The design must ensure that sufficient power and auxiliaries are available onboard to support the proper operation of the OCCS. In addition, stability review may need to be done due to the additional weight of the OCCS components. For new construction installation, the above issues can be well planned.
3. **Corrosion risk:** Certain OCCS technologies use chemicals for the separation process. In addition, impurities (especially water content) present in the captured CO_2 also cause corrosion issues. It is important to ensure that the materials used in the OCCS system along with tanks and piping components are to be suitable for the expected impurities and operational conditions.
4. **Risk of solidification:** One of the biggest risks when carrying CO_2 is the risk of solidification due to the pressures and temperatures falling below the triple point of CO_2. Therefore, it is important that the operating, storage and discharging parameters are well within the acceptable limits. It is important to note that the impurities present in the captured CO_2 affect the triple point of the CO_2. In this regard, any safety alarms and cutouts are to be set well above this triple point of the captured CO_2 and appropriate redundancies are to be provided to maintain the operational parameters.
5. **Risk to humans:** Although CO_2 gas is not a flammable gas, it is asphyxiant and in some cases could be toxic due to prolonged exposure at a higher concentration. In addition to the above, since the captured CO_2 may be carried at high pressure and low temperatures, proper safety features (e.g. personal protective equipment, additional ventilation, gas detectors, relief valves and safety cutouts) are to be provided to prevent over pressurization and potential failures.

Operational Challenges

1. **Handling of impurities:** Since the triple point of the captured CO_2 is affected by the impurities, it is important to ensure that the impurities are as minimum as possible. If there are insoluble gases in the captured CO_2, then the reliquification process is affected. Impurities in the CO_2 stream may also have an impact on the CO_2 density which may affect the design and operational parameters.
2. **Environmental effects:** The OCCS system is to be designed to be able to operate in extreme weather conditions. The failure of the OCCS systems and CO_2 storage is not to cause any adverse effects to the crew and environment. Leakage of chemicals or CO_2 into the atmosphere or overboard is to be avoided and properly contained except in case of emergency as determined by regulatory bodies. Robust monitoring and safety are to be provided to prevent unwanted discharges.
3. **Training of crew:** Since OCCS capture technologies may vary and due to the challenges of handling liquid CO_2, crew are to be properly trained in operating and maintaining the OCCS and CO_2 storage systems. Proper emergency handling procedures are critical in mitigating any damage or leakages and the crew is to be trained for these situations.
4. **Disposal of captured CO_2:** One of the biggest challenges today is the ability to offload liquefied CO_2 (LCO_2) to shoreside. There aren't many terminals available who have the ability and infrastructure to take CO_2. Usability of captured CO_2 is also limited but more research is underway to use captured CO_2 in the production of different products.

5. **Equipment failure:** Failure of the OCCS system is not to have any negative implications on the ship's propulsion. In case of emergencies or failure of the OCCS, a suitable bypass is to be provided to isolate the OCCS from the ship's engine exhaust system to allow for continuous operation of the engines. During operation of OCCS, the back pressure in the exhaust system is not to exceed the acceptable limits stipulated by the engine manufacturer.

Most of the challenges listed above have been addressed by existing classification rules and guidelines, as there are no international regulations in place yet. The next chapter will discuss how these challenges have been addressed. However, some areas remain that are not fully covered and require further evaluation. These also are covered in the following chapter.

Rules and Regulations for OCCS

Overview of existing regulations related to OCCS equipment and operations

There are currently no international regulations governing OCCS installations onboard ships (nor how to offload the captured CO_2 and transport it to an acceptable permanent storage site). This introduces uncertainties in terms of compliance requirements and standards, and it delays investment and adoption of OCCS technology by shipowners and operators. In the context of ongoing discussions, the regulatory framework for onboard carbon capture has seen some progress. Recent developments in safety and environmental performance regulations at IMO include:

Maritime Safety Committee (MSC)
Working Group on the Development of a Safety Regulatory Framework to Support the Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels (May 2024):

- The Group considered document MSC 108/5/1 (Republic of Korea), proposing the development of non-mandatory safety guidelines related to Onboard Carbon Capture and Storage (OCCS).
- While recognizing the merit of this proposal, the Group agreed that it would be prudent to first complete the development of a road map before deciding which sub-committees should be involved in preparing any new instrument or requirement.
- Therefore, the Group recommended that this proposal be kept in abeyance until a road map has been approved and is ready for implementation.
- Recalling that the Committee had already endorsed the HTW Sub-Committee's agreement to develop training provisions for seafarers on ships using alternative fuels, the Group discussed that the introduction of alternative fuels and new technologies would add new complexities to onboard ship systems. Therefore, further consideration should be given to the human element, crew training, and ship-specific familiarization.
- The Group concurred that crew members should be required to have ship-specific training when joining a ship to ensure safe operation and awareness of the challenges, risks, and complexities presented by these new and emerging technologies and fuels in both normal and emergency situations. The Group recommended bringing this information to the attention of the HTW Sub-Committee.

Sub-Committee on Carriage of Cargoes and Containers (September 2024)

- Liquefied CO_2 has been merged into one product name and identified as toxic for the purposes of the IGC Code. This was submitted to MSC 109 and then approved by the Committee.

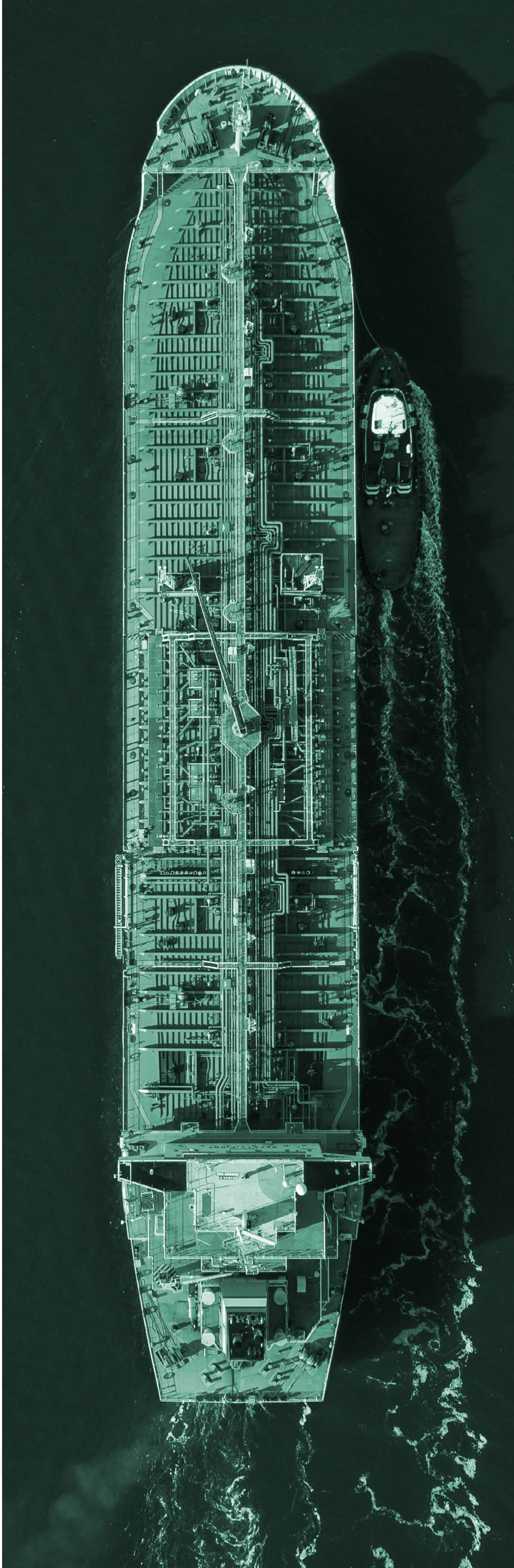
The Marine Environment Protection Committee (MEPC)
Working Group on Air Pollution and Energy Efficiency (March 2024)

Onboard carbon capture and storage was discussed at MEPC 81 by the Working Group on Air Pollution and Energy Efficiency. MEPC 81 established a Correspondence Group on measurement and verification of non-CO_2 GHG emissions and onboard carbon capture, to further consider issues related to onboard carbon capture, develop a work plan for a regulatory framework for the use of onboard carbon capture systems and report to MEPC 83 in 2025.

The Tank-to-Wake (TtW) methodology aims to quantify and evaluate the intensity of GHGs such as CO_2, CH4 (methane), and N2O (nitrous oxide) emitted onboard a ship, including emissions from fuel combustion, conversion, and all relevant fugitive emissions from the bunker manifold to the energy converter. Currently, TtW GHG emission factors are calculated using an equation that accounts for various factors, including the percentage of fuel mass that escapes without being oxidized and the emission conversion factors for CO_2, CH_4, and N_2O. The equation also includes terms for emission credits generated by biomass growth and carbon capture and storage (CCS), though some terms related to emission credits from captured CO_2 and the carbon source factor are pending further methodological guidance. The upcoming regulatory framework will further develop the TtW methodology to include detailed guidance on the calculation of emission credits from captured CO_2, ensuring that all emissions resulting from the process of capturing, transporting, and storing CO_2 are accurately accounted for. This approach will enhance the evaluation of the effectiveness of onboard carbon capture systems.

It is worth noting that several proposals have been put forward to integrate OCCS into existing regulatory frameworks at IMO. Below are key proposals aimed at achieving these goals:

1. Integration with Existing Regulatory Frameworks: Documents MEPC 79/7/4 (Liberia and ICS) and MEPC 79/7/22 (Republic of Korea) propose leveraging the advantages of OCCS technologies by incorporating them into the Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), and Carbon Intensity Indicator (CII) calculations. This integration aims to ensure that the carbon reductions achieved through OCCS contribute to improved ship parameters and overall emission reduction goals.
2. Amendments to EEDI Guidelines: Document MEPC 79/7/7 (China) suggests amending the current EEDI survey and certification guidelines to include the installation of OCCS. This amendment would allow the benefits of emission reduction from OCCS equipment to be formally recognized and accounted for in regulatory assessments.
3. Addressing Regulatory Gaps: Document MEPC 79/7/16 (Norway) highlights the need to address regulatory issues related to the use of OCCS. This includes ensuring responsible handling and management of captured carbon to prevent environmental harm. The proposal emphasizes the importance of developing comprehensive regulations that cover the design, testing, installation, and operation of OCCS under a unified international framework.



4. Research and Development: Documents MEPC 80/7 (RINA) and MEPC 80/INF.14 (RINA) provide examples of how OCCS can aid in decarbonizing the maritime industry through post-combustion CO_2 capture and storage. Although further research is needed to refine these technologies for onboard use, initial results indicate significant potential for emission reduction.
5. Proposal for Structured Review: Document MEPC 80/7/7 (China et al.) proposes a structured review of the regulatory framework for OCCS. This proposal includes developing a work plan to systematically address the regulatory needs and ensure the safe and effective implementation of OCCS technologies.
6. Urgent Need for Regulation: Chile, in its proposal, ISWG-GHG 16/4, underscores the urgency of initiating studies to develop regulations for OCCS. This includes addressing the potential environmental impacts of OCCS residues and emissions, as well as the transportation, storage, and disposal of captured carbon. Chile advocates for following the existing work pattern used for Exhaust Gas Cleaning Systems (EGCS) guidelines to expedite the development of OCCS regulations.
7. Environmental Impact Considerations: The proposals collectively emphasize the need to evaluate the environmental impact of OCCS. This includes assessing the potential for CO_2 leakage from storage sites and the effects on marine ecosystems. Ensuring that OCCS technologies contribute positively to GHG reduction without causing unintended environmental harm is a key consideration.

Overview of Existing Class Requirements for OCCS Eequipment and Operations

In the context of safety challenges with OCCS, which are described in the previous chapter, several class societies have developed prescriptive requirements for the design, construction, installation, and survey of machinery and equipment aimed at reducing CO_2 emissions from vessels and offshore units. In addition, they also offer various class notations for assets complying with these requirements and for assets that are designed for future OCCS installation and integration. The new requirements for OCCS have been developed based on the ideology applicable for Exhaust Gas Cleaning Systems (EGCS) and are applicable to installations on both new and existing vessels regardless of size.

Currently, only the amine-based carbon capture system requirements have been developed as it has the highest Technology Readiness Level (TRL). However, other technologies and novel concepts will be evaluated by the Goal-Based Standards process and accepted if they prove to meet the goals, functional requirements, safety, strength, principles, and the intent of the amine-based system requirements. One of the important parts of Goal-Based Standards process is to conduct a thorough Risk Assessment to identify the hazards, review the mitigations provided to ensure that the risks are either eliminated or reduced to an acceptable level. For the material selection, containment, refrigeration, liquefaction, and storage of liquid CO_2, compliance with the applicable requirements of the IGC code is required as stated in the documents. In addition, class rules and guidelines have also addressed various other important topics like the ship arrangement, system configuration, OCCS location, personnel safety, materials, structure, containment, piping, refrigeration plant, electrical, control and safety systems, vessel integration, and manufacturing and survey requirements due to their importance in maintaining the safety and integrity of the overall system. These topics address the safety challenges listed in the previous chapter.

To support innovation, where the use of other carbon capture technologies or deviation from the requirements is proposed, compliance with the goals and functional requirements is to be demonstrated. Risk assessment is a process to help demonstrate/justify that ‘risk’ from a proposed design can be ‘accepted’ by the class and the regulator (i.e. National Administration, flag), and to ensure that the overall level of safety provided is maintained (to eliminate/mitigate any adverse effect to the persons on board, the environment or the ship). Any appropriate solution can be provided which requires justification to demonstrate safe design and operation.

The following is a brief overview of requirements from MTF class members which have contributed to this report. We also acknowledge that other classification societies have developed and published requirements for OCCS.

ABS introduced the ABS Requirements for Onboard Carbon Capture and Storage system which provides classification criteria for the arrangements, construction, installation and survey of machinery, equipment, and systems for marine and offshore assets with installed post-combustion onboard carbon capture and storage equipment (Amine-based system) to minimize the risks to the vessel, crew and environment. Since the range of OCCS technologies may be broad, and may be combined with other EEA equipment, the applicable requirements will vary on a case-by-case basis. As part of these requirements, ABS offers different notations (mandatory and optional) depending on the level of readiness and risk assessments to identify hazards and ensure suitable mitigation is provided to minimize or eliminate the risks. These requirements are developed in association with the applicable requirements of the IGC Code relevant to CO_2.

ClassNK has published guidelines summarizing the safety requirements for the chemical absorption method using amine solution as the CO_2 absorbent and liquid storage of the captured CO_2. If CO_2 absorption method or a storage method other than the above is to be adopted, it will be examined on a case-by-case basis according to each design. These guidelines require that a risk assessment be conducted to understand the risks to persons on board, the environment, structural strength or ship integrity arising from the installation and use of CO_2 capture system. In addition, if the safety requirements are confirmed by applying these guidelines, a class notation can be affixed based on the application. Note that the affixation of a class notation can be applied as a ready notation to vessels for future CO_2 capture system.

DNV has developed the OCCS notation as a mandatory set of requirements for vessels with such installations on board. The notation addresses the key risks associated with such systems, focusing on absorption/desorption systems and storage of liquid CO_2 in particular. The rules are based on existing requirements for hazardous chemicals used in EGCS systems, main class requirements for refrigeration systems, and requirements and principles from both the IGC and IGF code as well as DNV gas carrier ship type rules, to address the risks introduced by the various parts of the systems. The requirements for the liquid CO_2 systems are made to accommodate the safe filling of liquid CO_2 storage tanks in operation, taking into account solidification, overfilling, and CO_2 toxicity levels and containment of leakages.

Lloyd's Register (LR) published and introduced rules requirements in the existing Part 5, Chapter 24 "Emissions Abatement Plant for Combustion Machinery and other Machinery and Equipment". It introduces rule requirements for the design, construction, and installation survey of EACCS (Emissions Abatement Carbon Capture and Storage) and also for preparation of a vessel to receive a 'READY EACCS' descriptive note. Requirements associated to the new class notation addresses the safety risks they may present to the vessel, covering aspects such as materials, structure, containment, piping, refrigeration plant, electrical, control, safety systems, vessel integration and manufacturing. Requirements associated to the READY descriptive note covers aspects related to the preparation of a vessel for the future installation and integration of an EACCS, such as structures, layout, interfacing, materials, electrical and safety systems.

Evaluate the safety of the Emissions Abatement Carbon Capture and Storage (EACCS) system and its integration with the ship's machinery, equipment systems, and other onboard systems during the installation phase. This evaluation should address hazards related to physical layout, operation, and maintenance, in compliance with LR's ShipRight Procedure for Risk-Based Certification (RBC). The process covering all phases, including initial Design and Safety, Risk Assessment (HAZID/HAZOP), Final Design Assessment based on the outcome of the Risk Assessment, Construction, Installation, and Commissioning Assessment, and In-Service Assessments.

Regulatory Gaps for Onboard Carbon Capture Systems

Despite the efforts of classification societies to close regulatory gaps, further evaluation and clarification are needed for the following topics. These items can be assessed as part of the larger carbon value chain ecosystem and require industry-wide understanding. However, in the context of the OCCS, the maritime sector and its specific requirements should be taken into consideration.

1. Carbon Dioxide Impurities

The impurities in the captured CO_2 affect the triple point which is important in deciding the operational and safety parameters. Moreover, the non-condensable impurities in the captured CO_2 affect the reliquefaction process. In this regard, the range of the chemical compositions in relation to the impurities within the CO_2 specifications intended for the project shall be considered when selecting the material for the CO_2 tanks and piping system.

Impurities in captured CO_2 may be different depending on the fuel used by the vessel and the carbon capture technology. Pure CO_2 is not assumed to be corrosive but in the presence of impurities, such as water, may form carbonic acid and can cause corrosion. Other impurities (SO_x, NO_x) in the CO_2 stream may also have similar effects. For general information, the following table (Typical CO_2 compositions) shows a food grade and captured grade of CO_2 specification.

Table 1 Typical CO_2 compositions [7].

Component	Northern Lights (ppm mol)[1]	EIGA food grade (ppm v/v)
Carbon Dioxide (CO_2)	Not specified	99.9% min.
Ammonia (NH_3)	≤10	2.5 max.
Argon (Ar)	Not specified	Not specified
Carbon monoxide (CO)	≤100	10 max.
Glycol	Not specified	Not specified
Hydrocarbons	Not specified	50 max. of which 20 max non-methane hydrocarbons
Hydrogen (H_2)	≤50	Not specified
Hydrogen sulphide (H_2S)	≤9	0.1 max. (total sulphur as S)
Methane	Not specified	50 max. of which 20 max non-methane hydrocarbons
Nitric oxide/nitrogen dioxide (NO_x)	≤10	2.5 max. each
Nitrogen (N_2)	Not specified	Not specified
Oxygen (O_2)	≤10	30 max.
Sulphur oxides (SO_x)	≤10	0.1 max. (total sulphur as S)
Water (H_2O)	≤30	20 max.
Amine	≤10	Not specified
Formaldehyde	≤20	Not specified
Acetaldehyde	≤20	Not specified
Mercury	≤0.03	Not specified
Cadmium, Thallium	Sum ≤0.03	Not specified

[1] Northern Lights CO_2 specification has been updated in February 2024 [8]

2. Toxicity

Currently, the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) classifies LCO_2 cargo as an asphyxiant and not toxic. However, based on industry developments and papers submitted to IMO, it is proposed to consider LCO_2 cargo as both toxic and asphyxiant. At CCC 9 the working group on the Review of the IGC Code discussed whether CO_2 could be considered as a toxic product. At the recently concluded CCC 10 [9], the working group on the Review of the IGC Code concluded that CO_2 would only be considered as toxic for the purposes of the IGC Code and not throughout other parts of SOLAS, which would be outside the scope of the group and may have unintended consequences. Currently, there are only a small number of dedicated CO_2 carrying gas ships transporting high purity cargoes, but it is anticipated that this will change, with a greater number of larger LCO_2 transport ships operating globally to transport parcels of captured CO_2 by sea to storage locations. As a result, the carriage requirements under the IGC Code for CO_2 have been modified with the vapor detection requirement changed from Asphyxiant (A) (i.e. checking for oxygen depletion) to Toxic vapor detection (T) (i.e. proactively checking for CO_2 itself) with a fixed gas detection system now also required for ships carrying CO_2 as cargo. Considering the volume/concentrations of CO_2 present on such dedicated CO_2 cargo ships, the consensus of the working group was that such safety precautions were appropriate. For dedicated CO_2 ships there were also logical amendments to fire protection system requirements given the characteristics of the gas.

Although in the case of carbon capture systems, the captured CO_2 is not a cargo, still the safety aspects of the IGC Code may need to be complied. It may also be relevant to note that, during CCC 10, a working group on the revised recommendations for entering enclosed spaces aboard ships (A.1050(27)) amended the recommendations to include recognition of the toxic nature of CO_2.

In the context of the quantities relevant for onboard carbon capture and storage, there should be a discussion as to whether it might be appropriate to have a carve-out for CCS systems from this toxic designation. Since CO_2 is designated as toxic, it will be a potential major roadblock for the implementation of these systems on non-IGC Code vessels. In addition, clarification is needed from IMO as to which requirements of the IGC Code are to be applied when carrying LCO_2 derived from onboard carbon capture systems.

3. Other onboard CCS technologies than chemical absorption

Currently, chemical absorption is covered by various class requirements, and other emerging technologies, including both pre- and post-carbon capture technologies such as Cryogenic, Membrane, and Calcium looping, etc. will be reviewed case-by-case based on a goal-based standard approach. Further, these are considered novel technologies that are not yet widely adopted. Prescriptive rules can provide clarity with the defined requirement, which helps the owners and designers meet the class requirements.

4. Crew Training

Crew training is the critical importance for the effective implementation and operation of OCCS. Detailed training programs should be developed to encompass both theoretical knowledge and practical skills. These programs must cover operational procedures, safety protocols, and maintenance requirements of OCCS. Additionally, the training should ensure that crew members are well-knowledgeable in the environmental regulations and standards related to onboard carbon capture. The objective is to equip the crew with the necessary expertise to manage OCCS efficiently, ensuring compliance with international environmental laws and safe operations.

The IMO Sub-Committee on Human Element, Training and Watchkeeping (HTW)discussed the development of training provisions for seafarers on ships using alternative fuels in February 2024. The Sub-Committee agreed that the existing output of MSC on "Development of a safety regulatory framework to support the reduction of GHG emissions from ships using new technologies and alternative fuels" could be utilized to develop relevant training provisions for seafarers, and invited MSC to include this output in the agenda of the Sub-Committee for discussion at HTW 11 in 2025 [10].

The Maritime Safety Committee, at MSC 108, endorsed the development of training provisions for seafarers on ships using alternative fuels. The Working Group on development of a safety regulatory framework to support the reduction of GHG emissions from ships using new technologies and alternative fuels emphasized the importance of ship-specific training for crew members to ensure safe operations and awareness of the challenges and risks associated with new technologies and fuels. MSC recommended bringing this to the attention of the HTW Sub-Committee [11].

5. Safety Management

Onboard procedures need to be adapted to account for the operational challenges of an OCCS, including maintenance and emergency procedures. According to the ISM Code, the development and implementation of the Safety Management System needs to reflect this, similarly as for other new technologies and alternative fuels. MTF raised concern about gaps in the implementation of the ISM Code and STCW Convention in a previous report [12].

Recommendations

To establish a robust framework for OCCS systems, we have identified several key recommendations tailored to relevant stakeholders. These recommendations are the result of a collaborative effort involving six partners. Our methodology is characterized by expert judgment and collaborative engagement. Furthermore, we have thoroughly reviewed existing reports, publicly available information, and documents submitted to the International Maritime Organization (IMO) and the European Union (EU). The review process is important for ensuring that our recommendations align with the most recent developments and regulatory requirements.

Policymakers/Flag states

1. **Develop Regulatory Frameworks:** Establish clear and consistent regulations that address the entire OCCS value chain, from onboard capture and storage to offloading procedures and long-term CO_2 management. This includes:
   a. Collaborate to develop trusted MRV schemes across the CO_2 value chain including the downstream infrastructure.
   b. Safety Guidelines for OCCS Installation and Operation: Develop safety guidelines specifically for OCCS, covering aspects like equipment design, risk assessment, crew training, and emergency response procedures.
   c. Consistently incorporate OCCS into existing regulations, such as the EEDI, EEXI and CII as well as into the EU ETS and FuelEU Maritime.
   d. Standardized CO_2 Quality and Impurity Limits: Define acceptable levels of impurities in captured CO_2 to ensure compatibility with different storage and utilization options while considering the fuel types used by ships.
2. **Provide Economic Incentives:** Implement policies to derisk OCCS investments and fund research and pilot projects for OCCS installation and incentivize innovation in this field.

Port Authorities

1. **Assess and adapt port infrastructure to accommodate OCCS operations, including:**
   a. Collaborate to develop certification schemes for downstream CO_2 reception facilities.
   b. CO_2 Offloading Facilities: Develop dedicated terminals or modify existing infrastructure to handle the safe and efficient transfer of LCO_2 from ships to shore.
   c. Temporary Storage Solutions: Provide enough storage capacity for LCO_2 at ports, considering the logistics.
   d. Integration with Transport Networks: Establish connections with CO_2 transport networks (pipelines, trucks, or ships) to facilitate the movement of captured CO_2 from ports to final storage or utilization sites.
2. **Collaborate closely with other Stakeholders:**
   a. Shipping Companies: Coordinate with shipping companies to understand their offloading needs, optimize scheduling to minimize disruption, and establish standardized procedures.
   b. Technology Providers: Work with OCCS technology developers to understand the compatibility
   between shipboard systems and port infrastructure, potentially through the development of common standards and procedures.
   c. Local Communities: Engage with local communities to address any concerns related to the handling and storage of CO_2 at ports.

Technology Providers

1. **Optimize System Design for Efficiency and Cost-Effectiveness:** Focus on developing OCCS technologies that:
    a. Reduce Energy Consumption: Develop energy-efficient capture and liquefaction processes, potentially through innovative materials, waste heat recovery systems, and process optimization.
    b. Lower Capital and Operational Costs: Explore cost-effective materials and fabrication methods to reduce the overall expenses associated with OCCS installation, maintenance, and energy consumption.
    c. Minimize Space Requirements: Prioritize compact system designs and efficient CO_2 storage solutions.
    d. Enhance CO_2 Purity: Develop technologies or processes that minimize the presence of impurities in the captured CO_2 stream, making it suitable for a wider range of downstream applications.

Shipping Companies

1. **Evaluate OCCS Feasibility:**
    a. Cost-Benefit Analysis: Analyze the economic viability of OCCS for their specific fleet and operational routes, considering factors like fuel costs, carbon pricing mechanisms, and potential cargo capacity trade-offs.
    b. Technical Compatibility: Evaluate the suitability of different OCCS technologies for their vessels, considering factors like space limitations, energy requirements, and integration with existing systems.
    c. Downstream CO_2 Management: Investigate accessing CO_2 storage or utilization facilities to manage the captured CO_2 effectively.
    d. Collaborate with technology providers to ensure the smooth integration of onboard and shore-based CO_2 management processes.
2. **Invest in Pilot Projects:**
    a. Gather Operational Data: Gain practical experience with OCCS operation, assess its performance in real-world conditions, and identify any potential challenges.
    b. Validate Cost and Efficiency Estimates: Verify the accuracy of initial cost projections and assess the actual energy consumption of OCCS systems.
3. **Update Safe Management, Crew Training and Awareness:**
    a. Amend the Safety Management System to include specifics of the OCCS operation, maintenance and emergency procedures.
    b. Develop OCCS-Specific Training Programs: for seafarers on the safe operation and maintenance of OCCS systems, including emergency response procedures.

Conclusions

This report highlights the potential of OCCS as a technology for reducing GHG emissions in the maritime sector, in line with global decarbonisation goals, including the IMO's target of net-zero emissions by 2050. The IMO is developing a regulatory framework for the safe adoption of OCCS, focusing on lifecycle emissions, but as of now, no international regulations fully govern OCCS. The European Union is expected to formalize its stance by 2027 under its "Fit for 55" climate package.

Key challenges for OCCS adoption include the need for a secure downstream infrastructure to offload, transport, store (or utilize) captured CO_2, as well as the need to reduce additional energy demand and system capital costs. Safety concerns, such as the toxicity and impurities in captured CO_2, also need to be addressed. This report calls for developing regulatory frameworks, standardized procedures for CO_2 handling, and safety protocols, alongside further research to enhance the cost-effectiveness, efficiency, and scalability of OCCS technologies. Stakeholders such as policymakers, flag States, technology providers, shipping companies and port authorities are encouraged to collaborate to build infrastructure, develop regulations, to develop OCCS as one means of achieving maritime decarbonization goals.

Overall, a successful implementation of OCCS necessitates a collaborative effort among all stakeholders, driven by a shared commitment to decarbonizing the maritime industry. By addressing the technological, economic, regulatory, and downstream value chain challenges outlined in the report, the shipping industry might benefit from the potential of OCCS to effectively reduce GHG emissions.

The report proposes several key next steps to facilitate the adoption of OCCS in the maritime industry:

1. Collaborate to create a secured downstream value chain comprising of CO_2 offloading facilities, transport infrastructure and long-term storage, together with associated MRV schemes, aiming that captured CO_2 emissions are permanently stored.
2. Establish clear and consistent regulations on safety and environmental performance, which include:
   a. Develop safety guidelines specifically for OCCS, covering aspects like equipment design, risk assessment, and emergency response procedures.
   b. Consistently incorporate OCCS into existing regulations, such as the EEDI, EEXI and CII as well as into the EU ETS and FuelEU Maritime.
   c. Develop certification schemes for downstream CO_2 value chain infrastructure.
3. Define acceptable levels of CO_2 impurities and develop standardized guidelines for safe CO_2 handling, including offloading procedures and port infrastructure requirements.
4. Amend the Safety Management Systems and develop specialized training programs for crew members covering the operation, maintenance and emergency procedures for OCCS systems.
5. Focus on development of OCCS technologies to increase CO_2 capture rates, reduce energy demand and, thus, increase cost-effectiveness and demonstrate OCCS systems in pilot projects to gather operational experience.

References

1. Maritime Technologies Forum (MTF), "Updated Fuels Evaluation Through The MTF Framework For Assessing Decarbonization Technologies", 2024.
2. S. Tavakoli, G. Malm Gamlem, D. Kim, S. Roussanaly, R. Anantharaman, K. Kusup Yuma and A. Valland, "Exploring the technical feasibility of carbon capture onboard ships," Journal of Cleaner Production, vol. 452, 2024.
3. IMO, "https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC-81.aspx," 2024. [Online].
4. European Commission, Questions and Answers on Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC, 2024.
5. European Commission, "Guidance Document: The EU ETS and MRV Maritime - General guidance for shipping companies", July 2024.
6. European Commission - Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'), 2021.
7. SIGTTO, "Carbon Dioxide Cargo on Gas Carriers (First Edition)", 2024.
8. Northern Lights, " Liquid CO2 (LCO2) Quality Specifications, NL-02-TE-SP01 Rev 1", 14 February 2024.
9. Sub-Committee on Carriage of Cargoes and Containers, 10th session, "Review of the IGC Code, Report of the Working Group", 2024.
10. IMO, "https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/HTW-10th-session.aspx," 2024. [Online].
11. Maritime Safety Committee, MSC 108/WP.8, " Support The Reduction of GHG Emissions from Ships Using New Technologies and Alternative Fuels - Report of the Working Group", May 2024.
12. Maritime Technologies Forum (MTF), "Operational Management to Accelerate Safe Decarbonization", 2023.

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