WHEN TRUST MATTERS

THE POTENTIAL OF ONBOARD CARBON CAPTURE IN SHIPPING

WHITE PAPER

Contents

Edition

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Executive summary

While many efforts to reduce greenhouse gas (GHG) emissions from shipping focus on improving energy efficiency of the vessels and switching to carbon-neutral fuels, another option is to capture the CO_2 produced by carbon-based fuels and utilize or store it in underground reservoirs. The carbon capture, utilization and storage technologies and value chains are under development to support decarbonization of land-based emissions, and the maritime industry is looking into its application on board ships. This white paper aims to provide guidance to shipowners, technology providers, and other stakeholders on central matters related to onboard carbon capture.

Technical feasibility and testing
The concept of onboard carbon capture is based on technology which captures the carbon on board the ship before the CO_2 is emitted to the atmosphere through the exhaust. Studies show that the technology can be applied safely on ships, but it still needs to be further developed and optimized for maritime use and integration. Key factors that affect the technical feasibility of onboard carbon capture for a dedicated ship are the size, operational profile and trading pattern, the machinery capacity for power and heat production, and the space available. Shipowners must investigate different decarbonization alternatives and should evaluate if onboard carbon capture could be a feasible option for their vessels. In general, an onboard carbon capture storage (OCCS) - ready thinking approach could be relevant to consider at newbuilding stage to reduce cost for future potential onboard carbon capture retrofit.

Commercial competitiveness
Onboard carbon capture's relevance for wider application by the shipping industry also depends on its commercial performance compared to other decarbonization alternatives. The application and uptake of onboard carbon capture technology depends on the relevant cost elements of the system, in addition to the regulatory and competitive landscape. In general, as long as decarbonization of shipping is enforced through regulations and market-based mechanisms, onboard carbon capture may be a commercially attractive solution if high capture rates, low fuel penalties, and low CO_2 deposit costs can be achieved.

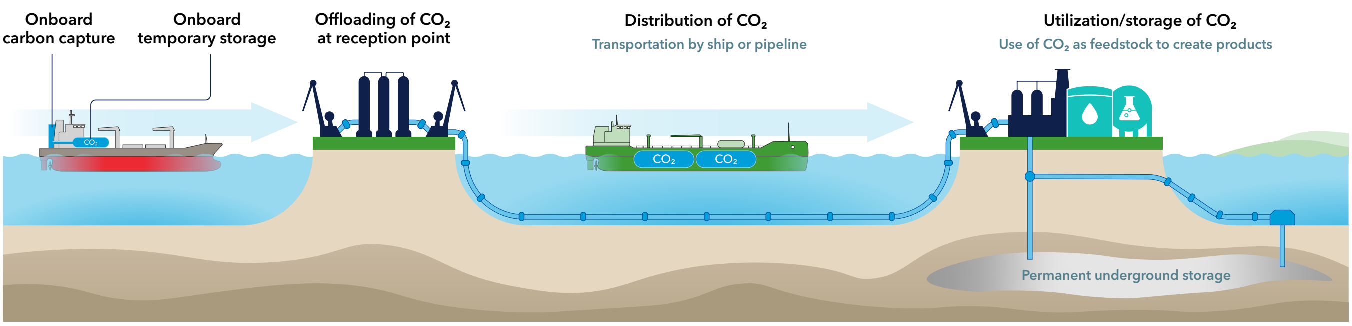
Regulatory approval
For shipowners to adopt onboard carbon capture, appropriate emission regulations must be established to credit captured carbon dioxide. Currently, the EU Emissions Trading System is the only regulatory framework incentivizing carbon capture on ships, which is in alignment with EU strategy on land-based CCS. In addition, the IMO has initiated a working group to look further into how onboard carbon capture can potentially be implemented in new GHG emission regulations. A continued push to quickly develop regulations that credit onboard captured CO_2 will reduce uncertainties for the industry and support further development.

Connection to the carbon capture, utilization, and storage (CCUS) value chain
A wide uptake of onboard carbon capture by the shipping industry is dependent on its integration within the broader CCUS value chain. A scaling of the CCUS infrastructure network, across geographies and nations, will establish the grounds for uptake of onboard carbon capture technology. As of today, this infrastructure is not established. The shipping industry needs to reach out to relevant CCUS development projects near major shipping hubs to discuss how the maritime industry can connect to the wider CCUS value chain.

DNV has been working on onboard carbon capture since 2009, and can support stakeholders wanting to investigate the feasibility of onboard carbon capture and its connection to the value chain.

FIGURE 1-1

Stepwise process of the onboard carbon capture value chain



1 Introduction

As the maritime industry prepares to meet updated and new regulations for decarbonization, demand for cost-efficient solutions is increasing. Candidate options include energy efficiency measures, alternative fuels, and onboard carbon capture (OCC). The latter is attracting increasing attention because it provides the opportunity to continue operation on conventional fuels, while reducing greenhouse gas (GHG) emissions. Currently, DNV participates in numerous large-scale onboard carbon capture technology pilots and feasibility studies and has already executed a range of Approval in Principle.[1]

For onboard carbon capture as a potential decarbonization solution, the industry is asking key questions about its marinization and implications:

- **Will it be accepted by future emission-related regulations, and under which terms and conditions?**
- **How and where can the captured CO_2 be disposed of, and how will this be handled in a full value-chain perspective?**
- **Is onboard carbon capture a technically and economically feasible option?**

This white paper reflects on these questions and aims to provide guidance to shipowners, technology providers, and other stakeholders on central matters related to onboard carbon capture. Figure 1-2 gives an overview of the necessary steps for the evaluation of the technology feasibility and commercial attractiveness related to onboard carbon capture vessel integration.

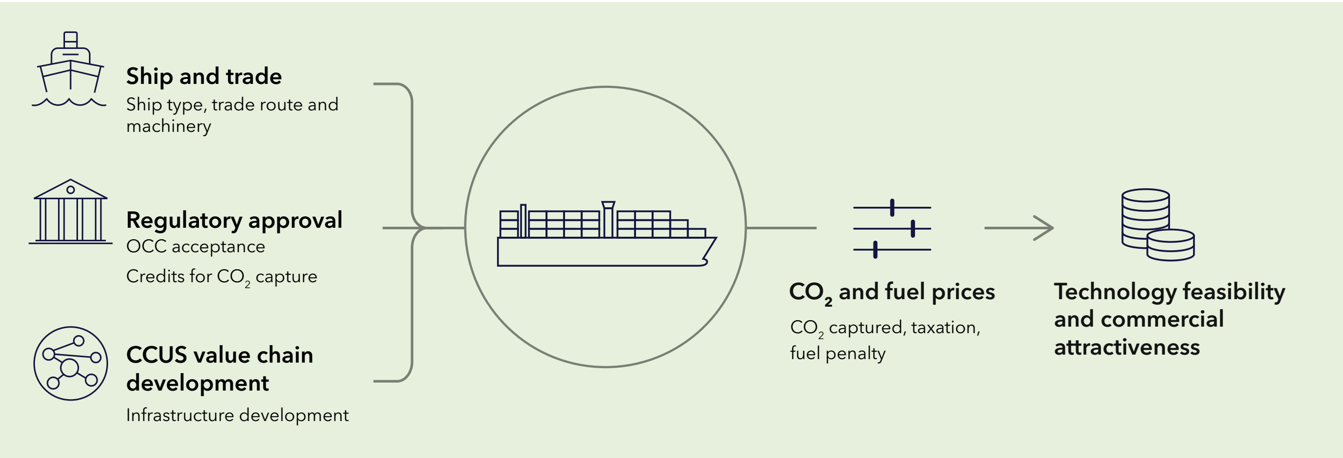
The paper covers the potential role that onboard carbon capture can play in the decarbonization of the shipping industry while also dealing with its integration in the broader developments of the carbon capture, utilization and storage (CCUS) value chain, which is essential for shipping.

A broad range of onboard carbon capture technologies are explored, and the impact of capture rates and fuel penalties discussed. In addition to economic influencing factors, we highlight practical considerations with regards to the implementation on board and in different ship segments – all affecting the commercial attractiveness of onboard carbon capture.

Environment, GHG emission and safety regulations surrounding onboard carbon capture are also outlined, providing insights into the current status and future directions of regulations that could impact the adoption and implementation of these technologies.

FIGURE 1-2

Evaluation of onboard carbon capture



1) Some examples of projects:
EverLoNG, https://everlongccus.eu/about-the-project
The Maritime CCS project (2009-2012)
The MemCCSea project (started in 2019)
The decarbonICE™ project (2019-2020)
Green Shipping Programme OCC Pilots: On tankers led by Altera Infrastructures, https://greenshippingprogramme.com/pilot/carbon-capture-and-storage-ccs-systems-on-board-vessels/ and on containers led by SinOceanic, https://greenshippingprogramme.com/pilot/carbon-capture-and-storage-ccs-systems-on-board-vessels

2 The role of onboard carbon capture

Scarce availability and potentially high cost of carbon-neutral fuels present significant hurdles to the decarbonization of the maritime industry. This chapter explores onboard carbon capture as a decarbonization option and touches on the challenges and considerations involved.

Given the urgency of global decarbonization, it is expected that the competition for green energy carriers in transportation may become challenging leading to higher fuel costs. DNV's Maritime Forecast to 2050 (DNV, 2023b) predicted that together with carbon taxes, the limited availability and high prices of low-carbon fuels could generate commercial grounds for onboard carbon capture.

Shipping companies will aim to ensure compliance through effective combinations of decarbonization options: carbon-neutral fuels, energy-efficiency improvements, operations optimization, and onboard carbon capture. Similar to what happened in the 2020s with the global sulphur cap, the after-treatment of carbon emissions is expected to be relevant for both existing ships and newbuilds.

Despite similarities with the SO_x scrubber case, onboard carbon capture bears additional challenges that may impact decision-making. One major challenge is the current lack of regulatory clarity on carbon emission creditability, which generates commercial uncertainty for shipowners. On the technical side, important considerations are the fuel penalty from system operation, and the practical implications for system installation, temporary onboard storage and disposal to shore. The trade-off lies between high capture rates of CO_2 and higher fuel costs due to additional fuel needed to capture the carbon dioxide. The onboard carbon capture investment and increased fuel costs need to be evaluated against the cost of emitting CO_2 and the cost of renewable fuel alternatives to reach emission targets.

Furthermore, the uptake of onboard carbon capture depends on the growth of a disposal network to receive and handle the capture process products. With the wider CCUS infrastructure in development, scaling up of the maritime carbon capture network will take time and is expected to reach a broader uptake after 2030. Disposal costs will be affected by carbon market developments, and especially the cost of transportation and storage of CO_2, which is reduced by the distance between emitter and storage (Clean Air Task Force, 2023).

While the onboard technology comes, it will require collaborative action involving regulators, policymakers, ports, class, suppliers and other industry stakeholders to make a difference.

3 Value chain developments

Shipping will need to integrate into the expanding CCUS network shaped by land-based point sources of CO_2 emissions. This chapter discusses how onboard carbon capture could connect to a future developed CCUS value chain and shows the global status of storage locations and capacities.

CO_2 emissions from land-based industry will drive development of the CCUS value chain, establishing the technologies and CO_2 purity requirements together with the transportation and storage providers. Shipping will have to fit into this chain as a branch, taking advantage of the expansion of CO_2 terminals near major ports. Special shipping services on a small scale may emerge to support CO_2 collection from ships around major hubs. The growth of such an infrastructure network is crucial for onboard carbon capture to increase.

3.1 From onboard capture to permanent storage or utilization

Onboard carbon capture systems will depend on a developed infrastructure for wider CCUS, as such capture will be the starting point of a long logistics chain. The onboard carbon capture value chain, as part of a greater value chain, is illustrated in Figure 3-1, with permanent storage as the endpoint.

FIGURE 3-1

A simplified maritime carbon capture and storage value chain from capturing and temporary storage of CO_2 on a ship or at an industry facility, offloading and ship transportation to permanent storage location

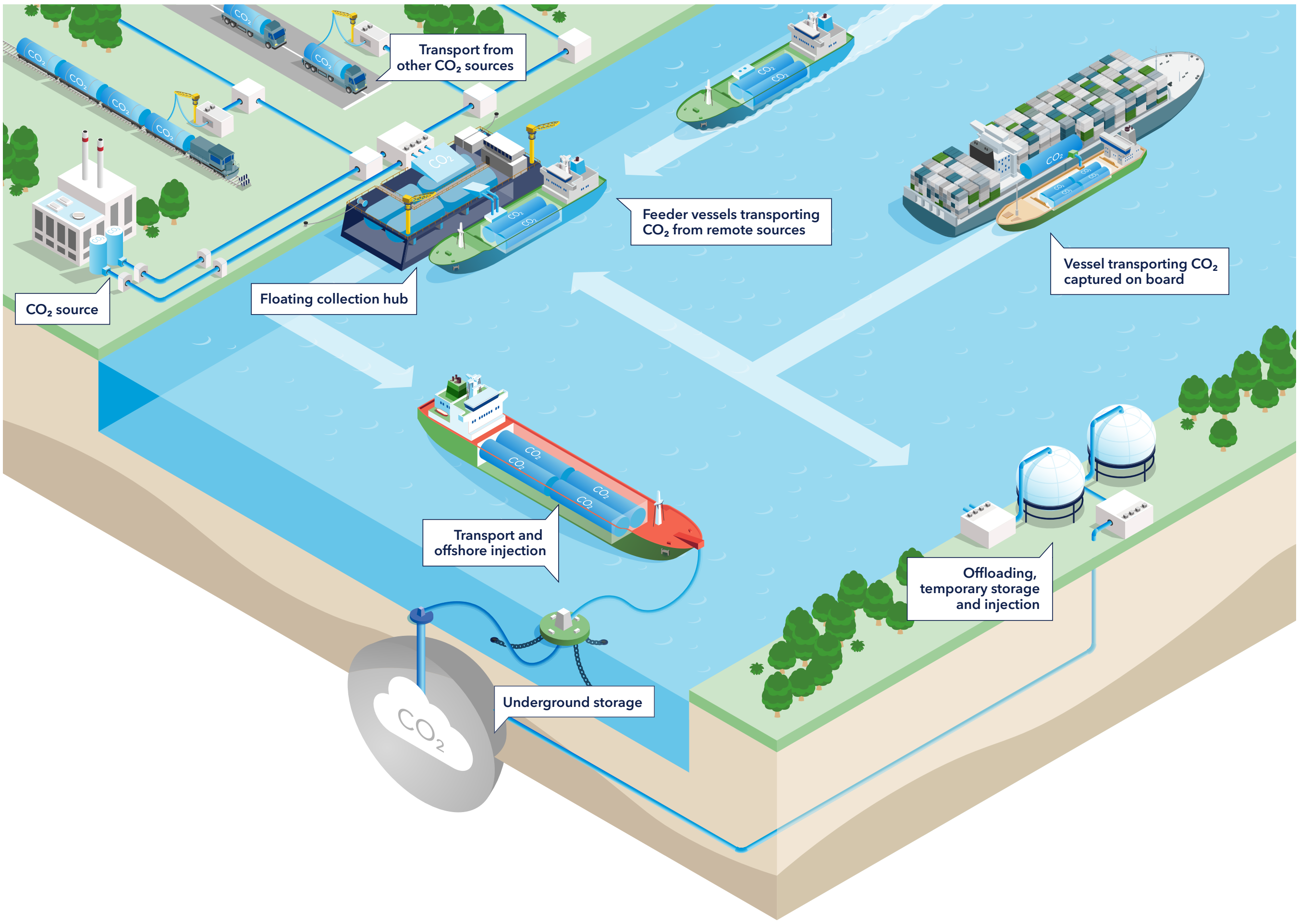
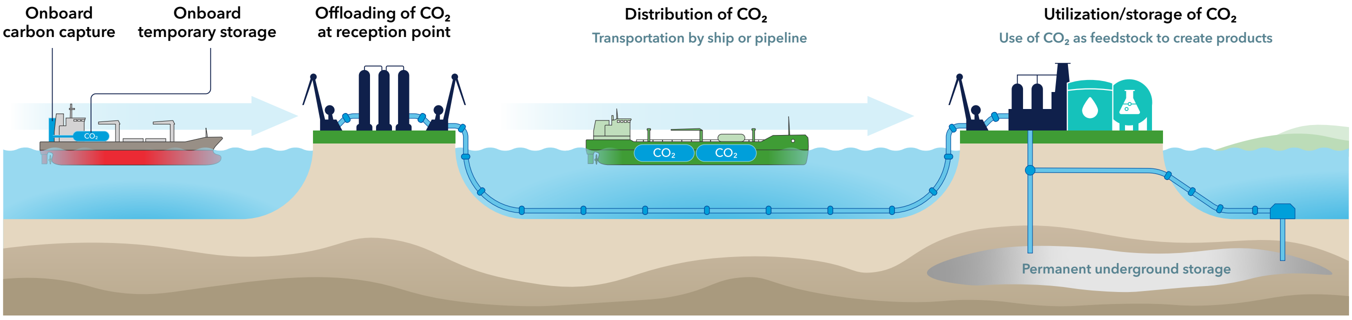


FIGURE 3-2

Stepwise process of the onboard carbon capture value chain



The five steps of this value chain are shown in Figure 3-2 with permanent storage or utilization as the endpoint. Details of steps 1 to 3 are covered in section 4.1.

Step 1 – Onboard capture: The ship will require a system to capture, remove and process the CO_2 to a state suitable for onboard storage. The captured carbon can be in various states, depending on the capture method: compressed gas, liquid, or solid (bonded in a mineral).

Step 2 – Onboard storage: The captured carbon is temporarily stored on board before being offloaded. Depending on the CO_2 state, different properties and containment systems are needed. In the case of liquid, the CO_2 product may be stored in IGC Type C tanks, following IGF code requirements, and the CCUS value chain properties.[2]

Step 3 – Offloading: Periodically, the ship will need to get rid of the captured carbon, either at the end of a voyage, or by making additional port calls or offloading to CO_2 carrying vessels. The offloading frequency depends on the trade and the availability of disposal facilities (e.g. CO_2 terminals, floating collecting hubs, and CO_2 receival vessels).

Step 4 – Transportation: After offloading, the CO_2 is transported to CO_2 reception facilities. In general, the CO_2 can be transported by ship and pipelines (but also trucks and trains). The facilities will be important nodes of the value chain, as further processing may be needed to prepare and condition the CO_2 stream to be compatible with the downstream CCUS value chain.

Step 5 – Permanent storage or utilization: The value chain ends with either permanent storage (sequestration) as waste or utilization. As waste, the captured CO_2 is permanently stored deep underground geological formations.

CO_2 properties and compatibility between the nodes in the value chain

The specification and condition of the CO_2 stream is an essential requirement for compatibility between the nodes of the value chain. Regardless of endpoint, the offloaded CO_2 must meet product specifications (e.g. purity, temperature, and pressure) dictated by the design characteristics of the offloading services and/or CCUS infrastructure. Also, purity standards will need to be met to ensure the integrity and reliability of the downstream CCS systems, and the interoperability of facilities to receive disposed carbon dioxide.[3]

2) Depending on the value-chain characteristics and the capture system selected, the CO_2 is required to be in different forms: liquid (captured in a liquid solvent), liquefied gas (medium or low pressure), gaseous (compressed gas), solid (captured through adsorption).
3) The Northern Lights project (https://norlights.com) is dedicated to medium pressure carriage of liquefied CO_2 for offshore sequestration. As part of the project, specifications of the CO_2 product were created, to ensure high-quality conditions that do not risk maintainability and operability of the systems. Important factors in the CO_2 specifications are the composition of non-dissolved species (N_2, O_2, Ar), and the level of acceptable contaminants (e.g. H_2S, NOx) and moisture (30 ppmol). The definition of the CO_2 stream properties is essential to avoid corrosion in the containment system, as well as predictable thermodynamic behaviour.

How to ensure permanent CO_2 storage?

While carbon capture and storage (CCS) has the potential to play a significant role in mitigating climate change, concerns about the security and permanence of CO_2 geological storage have been raised.

For geological storage of CO_2, it is fundamental to create confidence that the geological formations selected for the storage are suitable for the purpose, will deliver long-term emission reductions, and do not involve unacceptable risk. To ensure the permanence of a storage site, a thorough risk assessment and site characterization along with a suitable operations and monitoring plan are required. As every storage site is different, these assessments must be done on a case-by-case basis to minimize any risk of leakage.[4]

Permanent geological storage of CO_2 has been achieved since the 1996 at the Sleipner gas field in Norway with around 19 million tonnes stored up to 2022.[5] The Snøhvit CCS project has operated since 2007 and stored around 7 million tonnes up to 2022.[6] Both projects have had some issues with either injection or venting of CO_2 but are generally considered to show that permanent CO_2 storage is possible. However, most CO_2 injection to date has been used for enhanced oil recovery (since the 1970s), and leakages have occurred during the injection process[7], which highlights the need for rigorous risk assessments and operational planning to minimize risks.

3.2 Connecting onboard carbon capture to the CCUS value chain

The uptake of onboard carbon capture technologies will need to be linked to the development of the wider CCUS value chain development. Large onshore CO_2 emitters, such as industries that consume fossil energy or produce CO_2 as a by-product of their production processes (e.g. steel, cement, and fertilizers), drive the need for developing this logistics chain, as the volume from single onshore emitters is much larger than from an individual ship. Successful downstream integration of onboard captured carbon in the CCUS value chain depends on the ability to offload the CO_2 at convenient locations and then connect to carbon storage or utilization locations.

3.2.1 Status of carbon storage projects

By April 2024, 35 carbon storage projects were in operation worldwide with a total storage capacity of 37 million tonnes per annum (Mtpa), most of them related to natural gas processing and enhanced oil recovery (Alternative Fuels Insight (https://afi.dnv.com), April 2024).[8] Data on CO_2 storage capacities are also available from the Global CCS Institute (GCCSI, 2023). In general, the CCUS value chain is still at an early stage. Many projects for end-use and storage-related infrastructure for CO_2 are currently in the conceptual phase, with Final Investment Decisions (FIDs) expected in 2025 and beyond (GCMD, 2024).

Between now and 2050, the carbon storage capacity must be more than 100 times higher than the projected capacity for CO_2 storage if we are to reach net zero by mid-century.[9]

The forecasted global CCS capacity in net-zero policies' 2050 scenarios ranges from 4,000 to 8,400 $MtCO_2$ stored annually, part of which could be made available for CO_2 captured from shipping (Richardo & DNV, 2023). In comparison, shipping consumes about 3% of the world's energy and emits around 880 $MtCO_2$ per year.

3.2.2 Convenient disposal locations

Convenient reception points could be established near large bunkering hubs which can facilitate the development of terminal infrastructure and carbon-receival shuttle vessel services (similar to bunker vessels), or tailor-made disposal points for dedicated trades. Trades and routes with proximity (reasonable sailing distances) to hubs and carbon reception points will likely be more compatible with onboard carbon capture than others. For example, liner trades with fixed routes that call at major ports where CO_2 infrastructure is expected to be in place could more easily adopt onboard carbon capture than irregular spot trades.

To illustrate the potential CO_2 volumes to be offloaded in different ports, the planned CO_2 storage locations and capacities can be compared to the accumulated CO_2 emissions from ship voyages. Figure 3-3 shows the planned CO_2 storage capacities in 2030 as outlined in DNV's Alternative Fuels Insight (AFI) database. Figure 3-4 shows estimates on CO_2 emission from direct voyages into major shipping ports. The estimates are based on 2022 AIS data, applying a voyage-based approach that follows the vessels' movement from one port to another; a similar methodology is described in an AIS analysis from the Nordic Roadmap project (DNV, 2022).

4) Read more about DNV's work on CO_2 storage and use: https://www.dnv.com/focus-areas/ccs/carbon-storage-and-use
5) https://unfccc.int/documents/627398
6) https://www.miljodirektoratet.no/publikasjoner/2024/mars-2024/greenhouse-gas-emissions-1990-2022-national-inventory-report
7) https://www.worldoil.com/magazine/2003/january-2003/special-focus/co2-blowouts-an-emerging-problem
8) Operation and utilization of facilities within a year may differ from its nominal capacity potential. For reference in 2019, 25Mt of CO_2 was permanently stored worldwide.
9) https://www.irena.org/Energy-Transition/Technology/Carbon-Capture

FIGURE 3-3

Map of existing and planned global carbon storage projects in 2030, from the Alternative Fuel Insight (AFI) database (excluding enhanced oil recovery), by annual storage capacity (size of bubble) and location
Source: AFI (April 2024)

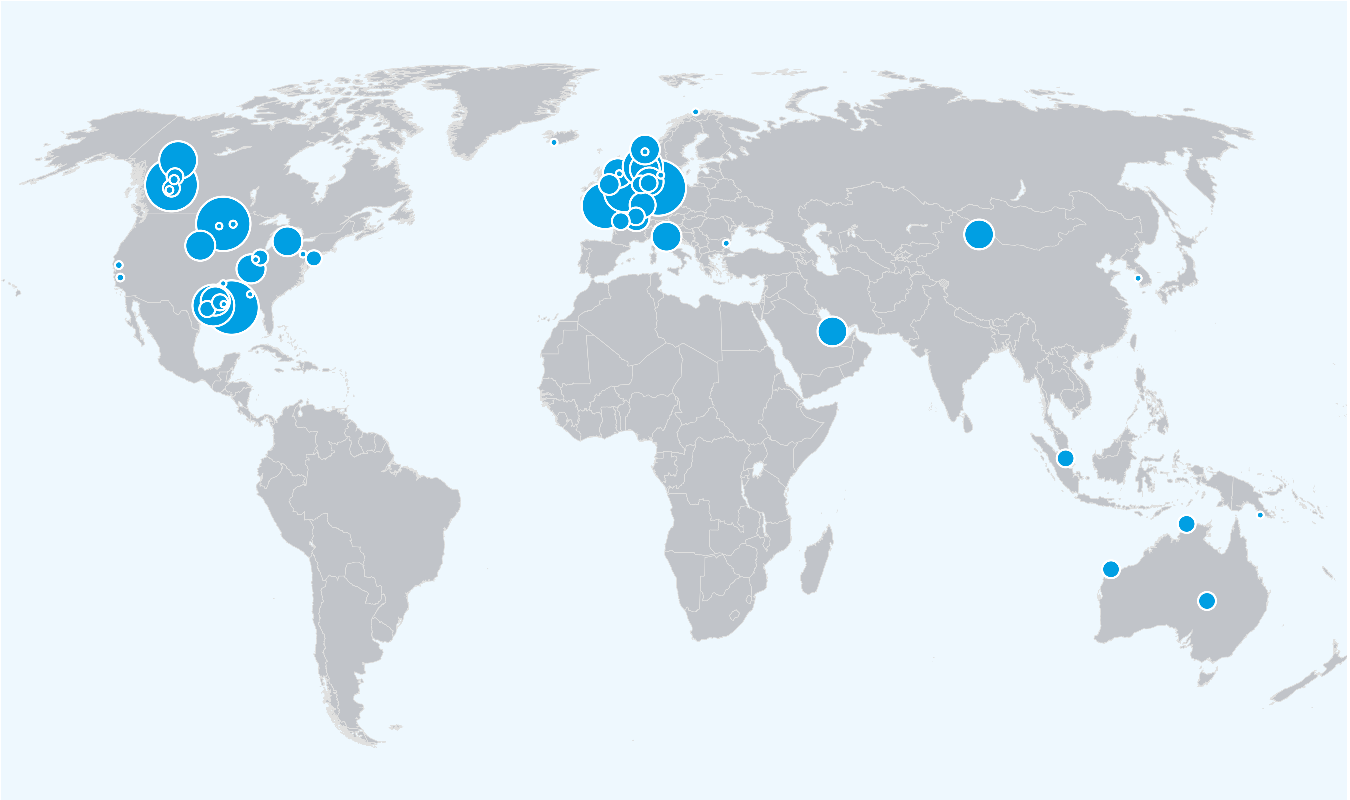
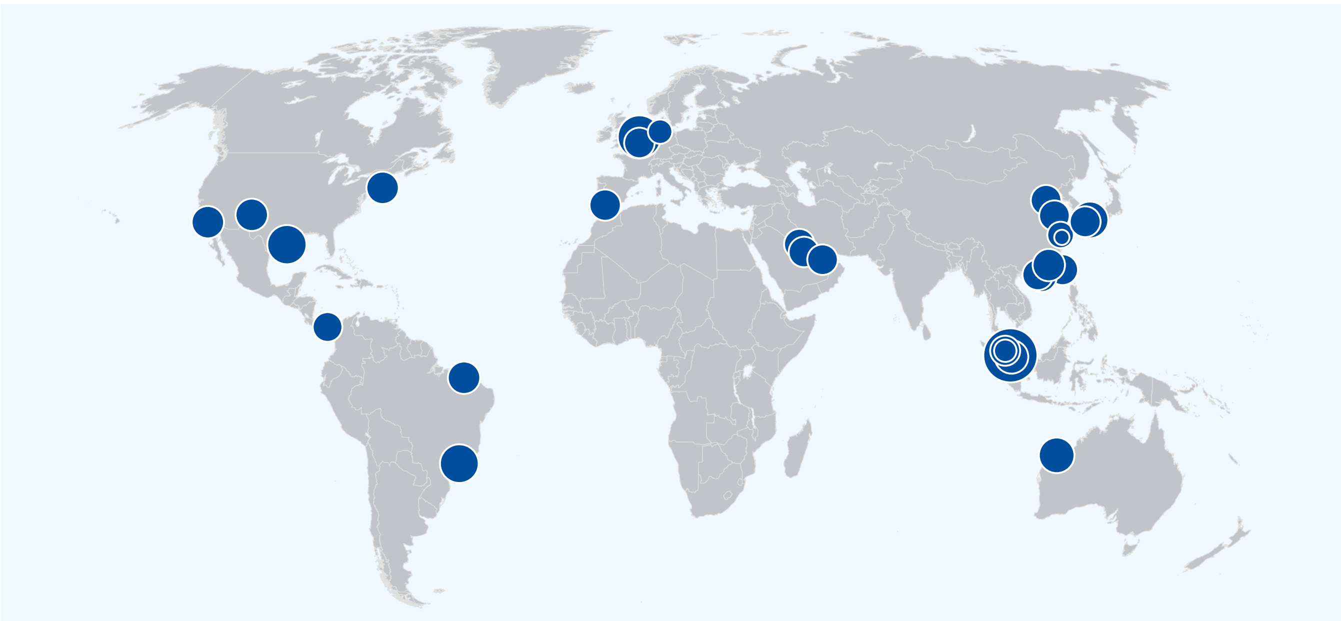


FIGURE 3-4

Voyage-based estimates of CO_2 emissions from direct voyages into major shipping ports, by annual tonnes of CO_2 emissions and location (AIS data, 2022)[10]



10) The estimates are based on 2022 AIS data, applying a voyage-based approach that follows the vessels movement from one port shape to another; a similar methodology is described in an AIS analysis from the Nordic Roadmap project (DNV, 2022). https://futurefuelsnordic.com/ais-analysis-of-the-nordic-ship-traffic-and-energy-use

The global network of CCUS will need to evolve to accommodate increased CO_2 volumes and the requirement for more geographically spread offloading facilities for shipping. Ships can be regarded as small-scale CO_2 producing units. However, as indicated in Figure 3-4, the accumulated annual volumes of CO_2 emissions in the busiest shipping locations are large even when compared with single onshore emitters. Singapore and Rotterdam are the two ports with largest accumulated annual CO_2 emissions from ship voyages into port, with around 24 and 13 million tonnes CO_2, respectively (2022 data). In comparison, the 10 largest announced projects for dedicated CO_2 storage have a planned capacity of 7.5–20 Mtpa (in 2030). With ports having the potential to collect and transmit such large amounts of CO_2 emissions, incentives to build out CCUS infrastructure and dedicated CO_2 storage for shipping in the most travelled shipping hubs should be considered.

The growth of onboard carbon capture-related infrastructure will depend on the development of networks of the CCUS value chain. The availability of disposal locations near shipping routes is a crucial factor for deciding to invest in onboard carbon capture.

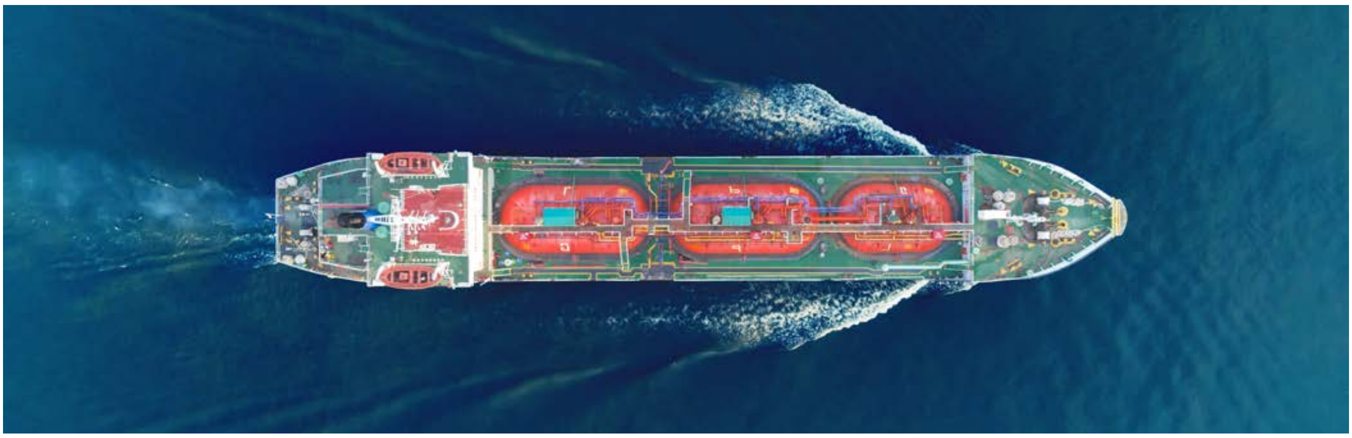
There are ongoing developments of CO_2 offloading facilities near port terminals; for example, at the ports of Rotterdam[11], Antwerp[12], Gothenburg[13], Gdansk[14], Dunkirk[15], and Wilhelmshaven[16]. Other initiatives are working to advance the value chains; for example, the Northern Lights project[17] that is developing CO_2 transport and storage facilities in the North Sea. In the Netherlands, the Porthos project is developing a value chain to transport CO_2 from industry in the Port of Rotterdam and store it in empty gas fields under the North Sea via pipelines.[18]

3.2.3 Demonstration and collaboration in closed value chains

To foster collaboration and coordination in the CCUS value chain, groups of stakeholders could work in closed value chains where they agree to share the costs and benefits of capturing, transporting, and storing CO_2. This can create a stable demand for CCUS services and reduce the risks and uncertainties associated with market fluctuations and policy changes. Closed value chains can also serve as green shipping corridors[19], with a coordinated development of supply and demand – showcasing the feasibility and impact of onboard carbon capture and CCUS as a decarbonization solution for the shipping industry.

Another way to accelerate the integration of onboard carbon capture and CCUS is to initiate dialogue with the larger CCUS projects that are in development, both in the short term and the long term. By engaging with these projects, the shipping industry can explore the possibilities and challenges of connecting ships to planned CCUS infrastructure, such as pipelines, hubs, terminals and storage sites. This can help to identify the optimal locations, technical specifications and contractual arrangements for CO_2 delivery and offloading from ships. It can also help to raise awareness and interest among the CCUS project developers and operators about the potential CO_2 volumes and revenues that can be generated from the maritime sector.

These approaches require first movers taking the lead in establishing partnerships and collaborations across the CCUS value chain. The first movers can gain a competitive advantage, enhancing their reputation and influencing the regulatory framework. However, they also face higher risks and costs, as well as technological and institutional barriers. Therefore, it is important to provide incentives and support for first movers, such as public funding, subsidies, guarantees, standards and regulations.



11) PORTHOS - Port of Rotterdam CO_2 Transport Hub and Offshore Storage, https://www.porthosco2.nl/en
12) Antwerp@C CO² Export Hub, https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/projects-details/43251567/101103080/CEF2027 https://safety4sea.com/eu-funds-co2-transport-project-at-port-of-antwerp-bruges
13) Large-scale CO2 hub in the Port of Gothenburg, https://www.portofgothenburg.com/about/the-port-of-the-future/large-scale-co2-hub
14) Poland – EU CC Interconnector, https://ec.europa.eu/energy/maps/pci_fiches/PciFiche_12.9.pdf
15) Dunkirk's CO2 hub, https://dunkerquepromotion.org/en/investments/7-dunkirks-co2-hub-the-first-co2-hub-in-france
16) CO2nnectNow, https://globuc.com/news/wilhelmshaven-to-become-co2-transport-hub
17) Northern Lights, https://northernlightsccs.com/about-the-longship-project
18) https://www.porthosco2.nl/en
19) DNV (2022), Insight on green shipping corridors - from policy ambitions to realization, Nordic Roadmap Publication No. 3-A/1/2022, https://futurefuelsnordic.com/wp-content/uploads/2022/11/Green-Corridor-Paper_Nordic-Roadmap.pdf

4 Onboard carbon capture

Various methods exist to capture CO_2. This chapter provides an overview of onboard carbon capture technologies, looking at possible capture rates and taking into account economic and design considerations. It also looks into the status of environmental, GHG emission and safety regulations needed to push the uptake of onboard carbon capture.

Onboard carbon capture is based on technology that captures the carbon in the fuel or the ship exhaust gas before CO_2 is emitted to the atmosphere. In principle, this can lead to significant emissions reduction, but at the expense of extra energy and storage space requirements. An illustration of onboard carbon capture components is shown in Figure 4-1.

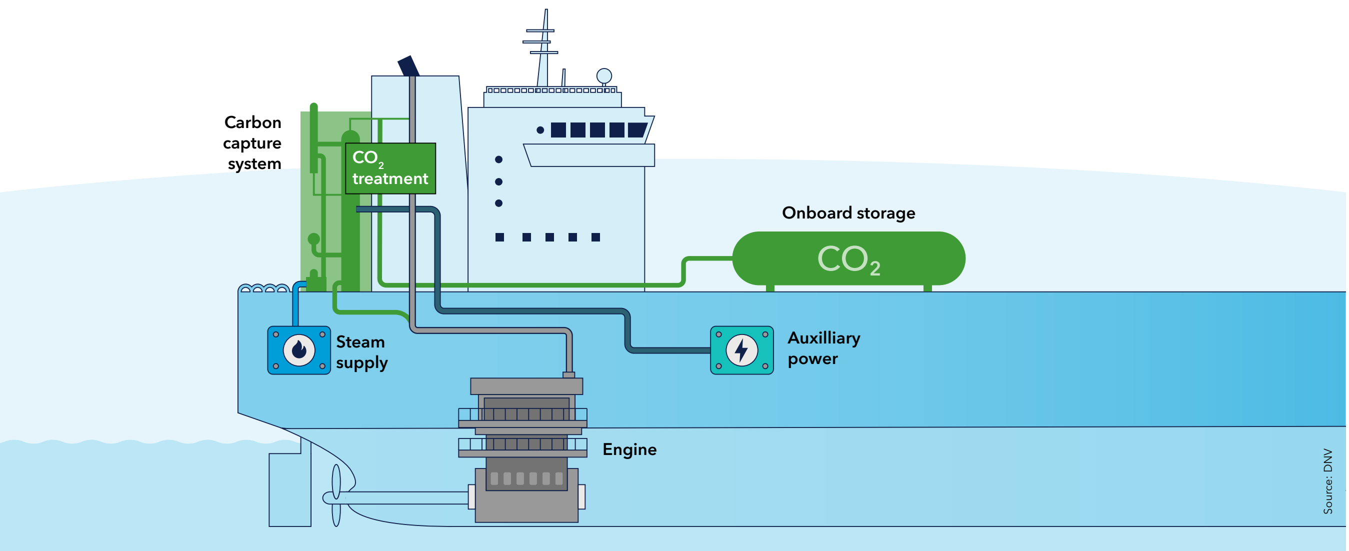
Ongoing pilots around the globe currently aim at filling the knowledge gaps around onboard carbon capture implementation. The Norwegian shipowner Solvang ASA is one of the early movers within amine-based onboard carbon capture. Solvang and Wärtsilä have received funding from ENOVA and will do a full-scale testing of a Wärtsilä carbon capture plant on an LPG carrier.[20, 21] The goal is to demonstrate that CO_2 can be captured from heavy fuel oil combustion and stored on board in deck tanks, and to gain experience on operational aspects of the process, energy consumption, and maintenance needs.

EverLoNG[22] is a three-year EU research initiative involving maritime industry stakeholders, DNV and R&D, and is co-funded by the ERA-NET ACT3 programme. The project aims to encourage the uptake of onboard carbon capture and storage by demonstrating its use on LNG-fuelled ships and moving it closer to market readiness. The work tasks include demonstrating onboard carbon capture and storage effectiveness by installing test installations on two LNG-fuelled vessels, evaluating the cost of onshore logistics, and developing a roadmap proposal for a European CO_2 offloading network.

The Ermafirst – Neptune Lines demonstration project was initiated in 2023 with an Approval in Principle by DNV and continues with a dedicated conversion pilot, focused on the onboard capture plant on a RoRo ship.

FIGURE 4-1

Simplified illustration of subsystems in an onboard carbon capture system based on their functionality



20) https://solvangship.no/2021/10/19/solvang-signs-deal-to-decarbonise-fleet-2
21) https://maritime-executive.com/article/solvang-orders-world-s-first-full-scale-onboard-carbon-capture-retrofit
22) https://everlongccus.eu/about-the-project

4.1 Onboard carbon capture technologies

The onboard carbon capture technology space is currently expanding with a wide range of concepts, which could be divided mainly into two categories: pre- and post-combustion (Figure 4-2). In pre-combustion, the carbon is removed from the fuel before combustion, while in post-combustion, CO_2 is removed from the exhaust gas stream. Oxy-fuel combustion is a third category, which refers to oxygen-rich combustion with exhaust recirculation, resulting in CO_2-rich exhaust and the release of CO_2 as a by-product. The latter is relevant to fuel cells as energy converters, whereas post-combustion is more relevant to conventional machinery such as internal combustion engines (ICE). There is ongoing work for including the uptake of onboard carbon capture technologies on the AFI platform (https://afi.dnv.com).

4.1.1 Capture methods

The most relevant method for conventional marine energy systems is post-combustion, where carbon is separated from the exhaust after combustion. Table 1 shows an overview of different post-combustion capture methods. These use various mechanisms, such as chemical absorption, adsorption, and membrane-based or cryogenic separation. The concept of post-combustion carbon capture (example: amine absorption process) is illustrated in Fig 4-3.

Chemical absorption with amine solvents is one of the most advanced options, with a long history of use in onshore applications. Marine examples are currently testing its feasibility for ships. For fuel-cell systems with LNG as fuel, pre- or oxy-fuel combustion are possible capture methods.

In the pre-combustion case, the LNG fuel is reformed before combustion to produce hydrogen and carbon dioxide. The hydrogen is utilized in fuel cells for energy conversion, while the CO_2 is captured and processed. This concept can be combined with other systems, such as conventional marine engines, to create designs where the fuel cell acts as both the energy converter and the CO_2 separator. In the oxy-fuel case, the systems use pure oxygen and gas recirculation, resulting in high CO_2 exhaust. These concepts are not well-developed in shipping, affected by the low adoption of fuel cells in the market.

FIGURE 4-2

Graphical representation of onboard carbon capture technologies by system features and relevance to the type of energy converter and fuel

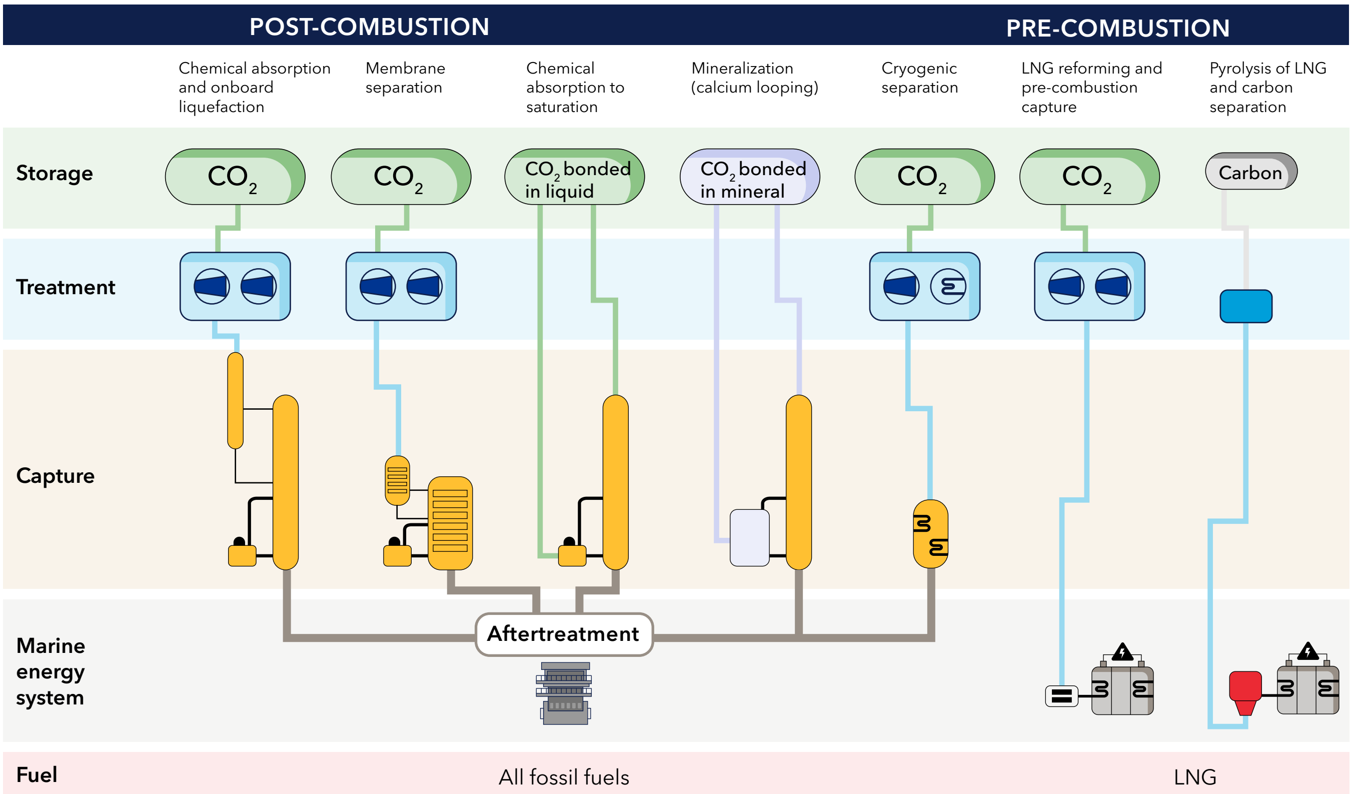


FIGURE 4-3

The concept of post-combustion carbon capture – the example of an amine absorption process

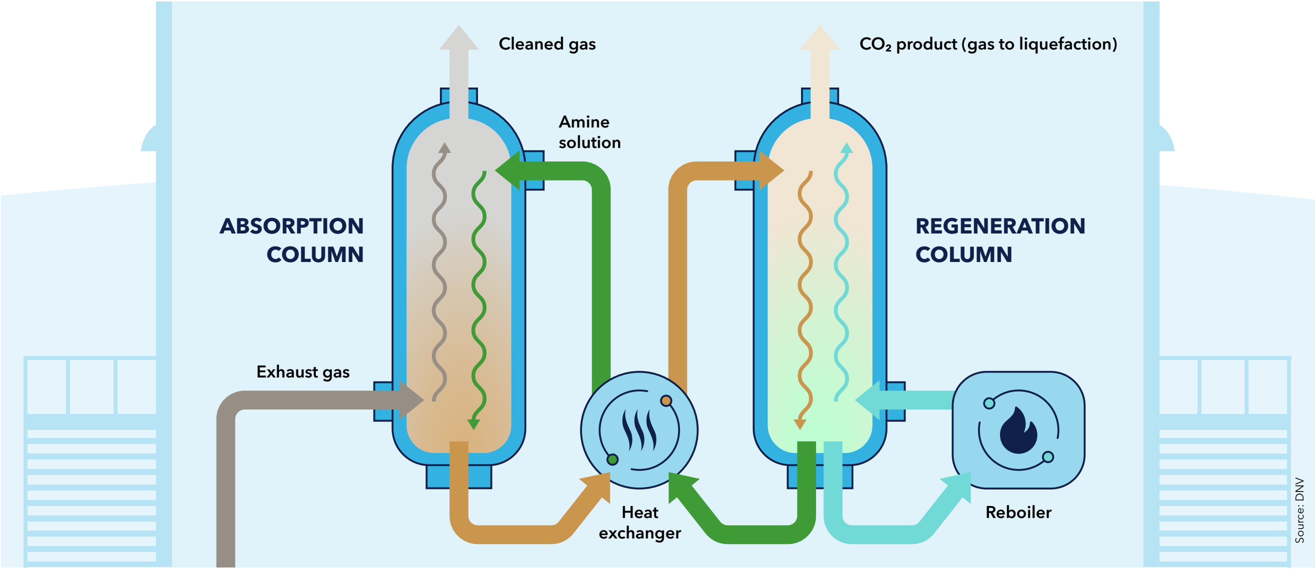


TABLE 1

Overview of post-combustion capture methods

Chemical absorption	The exhaust gas stream is scrubbed by a liquid solution, comprising of a chemical agent and water, such as amines. CO_2 is selectively absorbed into the liquid, where it is bonded by the chemical compound and thus removed from the exhaust. The clean gas stream leaves the system, while the liquid solution saturated with CO_2 is either recirculated in the system or regenerated – to release CO_2 gas. The regeneration process is energy consuming, requiring significant amounts of heat, between 3–4 GJ/tCO_2 for conventional solvents. Novel solvents can achieve improved performance of 2 to 2.5 GJ/tCO_2 (T. Damartzis, et al. 2022). When CO_2 gas is generated, proper treatment and handling is required for temporary onboard storage until discharge. The CO_2 gas can either be compressed and pressurized, or most often liquefied under medium or even low-pressure conditions. Onboard carbon capture involves cleaning of exhaust gases from CO_2, separating the CO_2 and storing it on board in various forms, depending on the technology (gas, liquid, or mineral), before offloading.
Membrane separation	The exhaust gas stream passes through membrane modules that selectively allow CO_2 to transport through their structure and become separated from the exhaust. The cleaned gas leaves the system, while the CO_2 stream is led to the treatment system, to become either compressed gas, or liquid. Some market concepts combine membranes and liquid absorption, to ensure increased mass transport efficiency, and reduced space requirement and regeneration energy demand on board.
Cryogenic separation	The exhaust stream is cooled down until CO_2 is separated into liquid and solid forms. As a result, CO_2 is separated from the gas constituents (e.g. nitrogen and oxygen) that require significantly lower temperatures to solidify. Impurities like water may separate out earlier than carbon dioxide. Effectively, the CO_2 product has high purity. The separation of phases is achieved by centrifuges, for example, and hence requires electric power for the cooling and compression unit.
Mineralization (calcium looping)	Depending on the concept design, the exhaust gas is passed through a reactor, where minerals are used to bond CO_2 into their structures, removing it from the exhaust gas. The saturated mineral is gathered as deposited sludge, which is offloaded at the port. The concept involves storage areas for both the mineral and the saturated product.

4.1.2 Balancing capture rate versus fuel penalty

Capturing carbon onboard ships is associated with the use of energy needed to operate the carbon capture and treatment system, usually in the form of heat and electricity. This energy demand may lead to additional fuel consumption. The fuel penalty depends on the type and performance of the capture technology, as well as the ship's operating profile and engine load. The trade-off between high capture and low fuel penalty is one of the main challenges of onboard carbon capture, as it affects both the environmental and economic viability of the technology. Systems operating with a high capture rate may have excessive energy demands, making them less feasible from an operational and cost perspective.

Figure 4-4 shows the impact of an onboard carbon capture system on baseline emissions, illustrating the captured CO_2 versus the extra CO_2 emissions, because of the fuel penalty.

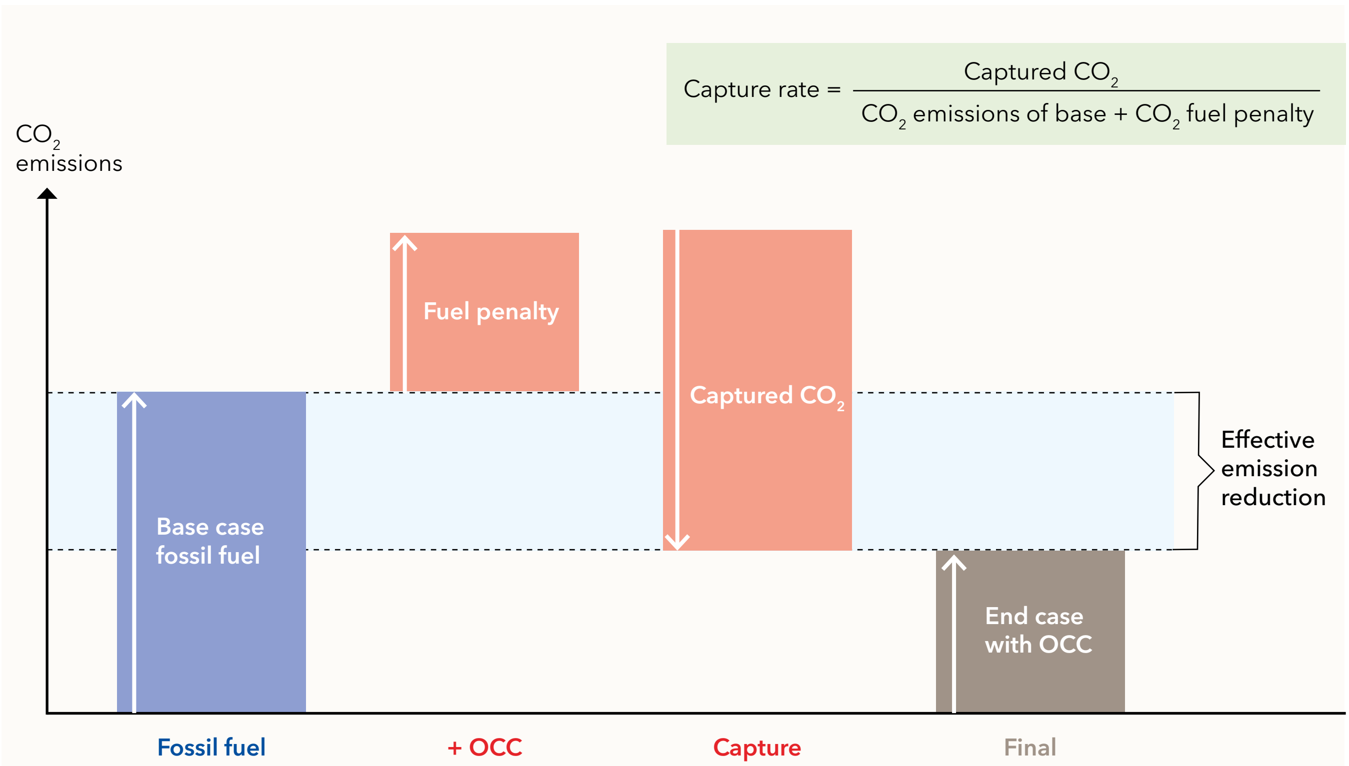
Fuel penalty refers to the additional fuel needed to run the capture and processing system on board. The fuel penalty, typically estimated to be in the order of 10% and 40%, depends on the capture method and capacity. Indicatively, for conventional amine scrubbing technologies, the fuel penalty is caused by the extra heat for solvent regeneration, and the electric power to run the fluid pumps, the exhaust gas force draft fan, and the CO_2 liquefaction plant.

Capture rate refers to the percentage of CO_2 captured against the total emissions of the vessel, including the extra energy and emissions to run the carbon capture system. With conventional carbon capture technologies, a 100% capture rate may be unrealistic; however, net-zero emissions can be achieved by combining onboard carbon capture with blend-in of carbon-neutral fuels. The capture rate is limited by several factors, including the following:

- Capture technology and space requirements for on board application.
- Available space and weight on board.
- Energy demands of the technology.
- Machinery system power and heat supply resources, in terms of extra electric power and thermal supply.
- Ship type and trade, with emphasis on the number of frequent port calls.

FIGURE 4-4

Illustration of carbon emissions and reduction by use of an onboard carbon capture (OCC) system



A higher capture rate means more CO_2 is prevented from being released into the atmosphere, which improves the environmental and GHG emission performance of the vessel. However, a higher capture rate may also require more energy (increasing the fuel penalty) and more onboard space for the capture and storage system, potentially reducing cargo capacity. Therefore, finding the optimal balance between capture rate, fuel penalty, and other operational considerations is key to making onboard carbon capture a feasible and effective solution. Capturing carbon can be a measure to comply with the upcoming GHG regulations, following a decarbonization trajectory and minimizing costs.

One way to balance the trade-off between high capture rate and low fuel penalty is to optimize the capture rate according to the ship's route and the availability of CO_2 offloading facilities along the way. For example, a vessel that operates in a region with a dense network of offloading stations can potentially reduce the intermediate need of CO_2 storage on board. Additionally, the capture rate can be adjusted based on the carbon intensity of the fuel used, such as LNG, and the emission regulations of the areas where the ship operates, such as Emission Control Areas (ECAs) or zones for carbon pricing.[23]

Fuels containing less sulphur oxides (SO_X) and particulate matter (PM), such as LNG fuel, require less exhaust pre-processing and hence smaller and more efficient capture plants (Sustainable Ships, 2023). Furthermore, the integration of the LNG fuel handling system with the CO_2 liquefaction line can also be investigated, to exploit cooling load and reduce liquefaction demands.

Innovations such as the use of centrifugal forces or membranes (MemCCSea, 2013) can improve mass transport and reduce energy demands. Additionally, waste heat recovery can help reduce heat demand. Onboard heat and power integration can be optimized in the case of newbuildings (DNV and PSE, 2013), and improved in the case of retrofits, through solutions like exhaust gas economizers for additional heat production. Improved carbon capture systems can also reduce the sensitivity to impurities in the exhaust stream, resulting in less power demand on board.

Capture technology integration with the rest of the ship machinery system is essential to enhance the overall performance and reduce the fuel penalty. The fuel penalty to produce heat can be significantly reduced by the utilization of advanced waste heat recovery from the ship's main and auxiliary engines. Further, internal optimization and heat recuperation of the onboard carbon capture system is necessary to minimize the external heat input, and hence the additional fuel. The electric power demand by onboard carbon capture is mainly related to processing captured carbon dioxide. Again, CO_2 processing optimization, usually a liquefaction cycle, is critical. The introduction of shaft generators and/or waste heat recovery via turbogenerator can reduce further the fuel penalty. The above indicates that the methods and technologies associated with reducing the fuel penalty of onboard carbon capture may incur higher levels of capital expenditure for the whole vessel.

Solvang and Wärtsilä intend to use Clipper EOS for full-scale testing of onboard carbon capture and storage (Photo rendering by courtesy of Wärtsilä and Solvang Shipping)

23) https://carbonpricingdashboard.worldbank.org

4.2 Economic considerations

For onboard carbon capture to be a feasible option in the decarbonization of the maritime sector, its commercial performance must be competitive compared with other decarbonization alternatives. There are large uncertainties related to the cost of onboard carbon capture since the technology and its onboard integration are still quite immature for maritime use. The application and uptake of onboard carbon capture technology on vessels is dependent on cost and price factors, as indicated below.

Cost factors

- **Capital costs:** The system capital expenditure (CAPEX) includes the costs of the capture unit, liquefaction, storage tanks, outfitting, piping, design and installation.
- **Fuel penalty:** The additional fuel consumption due to the fuel penalty will increase the fuel costs.
- **Operating costs:** Maintenance and replacement of solvents used in the capture process is expected to pose additional operation costs.
- **Loss of cargo carrying capacity:** The system space requirements (depending on capture rate, disposal frequency, etc.) can lead to loss of cargo space and hence loss of income.
- **Carbon discharge costs:** The cost of offloading the captured carbon to the reception facilities is expected to depend on the broader CCUS value chain cost, for CO_2 transport and storage.

Price factors

- **Carbon pricing:** Mechanisms like the GHG emissions allowances under the EU Emission Trading system (ETS) will influence the attractiveness of onboard carbon capture; the higher the CO_2 price, the better the business case.
- **Fuel prices:** Lower fossil fuel prices will reduce both the main fuel cost and the additional cost from the fuel penalty and make onboard carbon capture more attractive. Whereas cheaper carbon-neutral fuel will make onboard carbon capture less attractive. The low availability of carbon-neutral fuels, and shipping competing with other industries for these fuels, are also factors that influence the competitiveness of onboard carbon capture.

There are two essential aspects when evaluating the commercial attractiveness for onboard carbon capture:

- Cost for emission of CO_2 (CO_2 tax), for example the EU ETS.
- Other drivers for decarbonization enforcing reduction of CO_2 emissions.

If taxing CO_2 is the only incentive to reduce emissions, the cost of emitting CO_2 will need to be higher than the total cost for capture and discharge. However, with other drivers for decarbonization, such as emission compliance (CII and upcoming IMO policy measures, Poseidon Principles, etc.). Decarbonization is not an option but a requirement and ticket for continued operation. The commercial evaluation then becomes a comparison between the different decarbonization alternatives and not only about carbon tax.

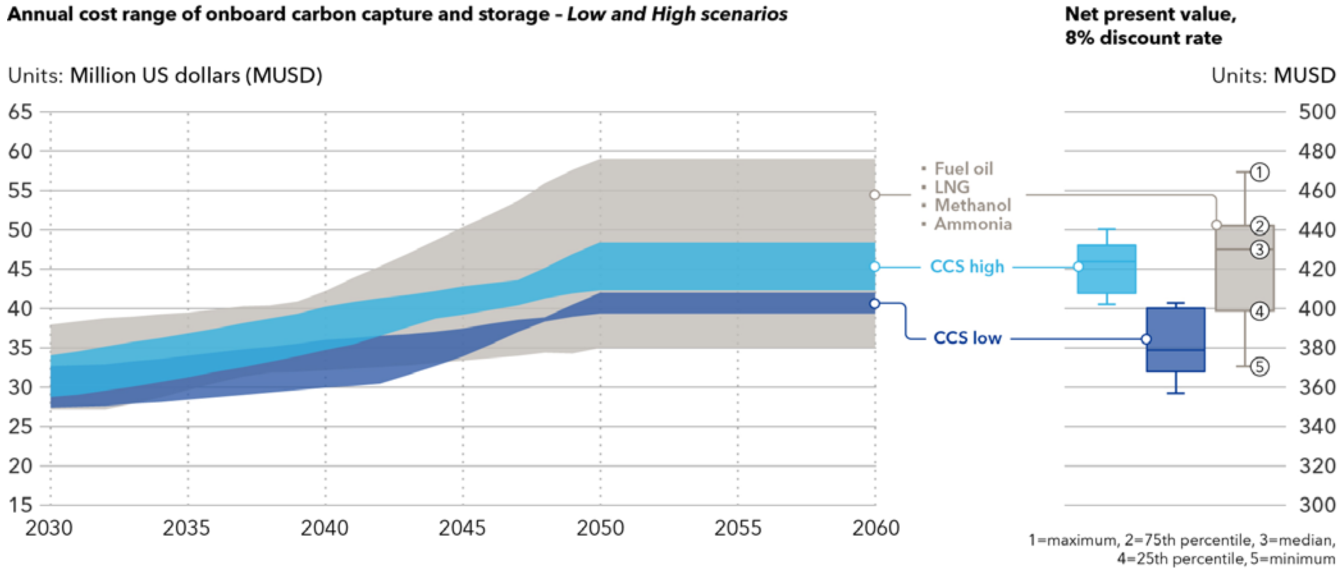
In Maritime Forecast to 2050 (DNV, 2023b), the commercial feasibility of onboard carbon capture was evaluated against carbon-neutral fuel alternatives for a 15,000 TEU container vessel (Figure 4-5). The study compared four fuel strategies (fuel oil, LNG, methanol, and ammonia) against onboard carbon capture with a 70% capture rate. The case study showed that onboard carbon capture was economically viable for a low-cost scenario (15% fuel penalty and deposit cost of 40 USD/tCO_2), and competitive for a high-cost scenario (30% fuel penalty and deposit cost of 80 USD/tCO_2). Another DNV study investigated the economic viability of onboard carbon capture on LNG carriers, considering the sensitivity of capture rate, fuel penalties and disposal costs (DNV, 2023a).

For more information please click here or scan the QR code.

If onboard carbon capture technologies can reach low fuel penalties and the CCUS industry can offer low CO_2 deposit costs, onboard carbon capture will be an economically competitive decarbonization strategy.

FIGURE 4-5

Range of case study annual costs (left) and net present value (right) for Low CCS and High CCS onboard carbon capture scenarios compared to the benchmark from the Maritime Forecast to 2050 (DNV, 2023b)



4.3 Regulatory status

For shipowners to choose onboard carbon capture, emission and safety regulations must be in place to ensure that the emission reductions are credited in the regulations.

4.3.1 Environmental and GHG emission regulations

Today, the EU ETS is the only adopted regulatory framework which provides incentives for the use of carbon capture on board ships. However, there are ongoing discussions at the International Maritime Organization (IMO) and EU levels for updates on the matter:

- **IMO:** Currently, there are no regulations that include provision for onboard carbon capture in MARPOL or other instruments. At MEPC 81 in March 2024, the IMO agreed to develop a detailed work plan for establishing a framework to regulate onboard carbon capture technologies.
- **EU ETS:** EU ETS (Directive 2003/87/EC) includes a derogation exempting emissions that are verified as captured and transported for permanent storage to a facility having a permit under the CCS Directive (Directive 2009/31/EC). In May 2023, the EU added a similar provision (Directive 2023/959) for GHG emission captured and utilized in such a way that they have become permanently chemically bound in a product so that they do not enter the atmosphere under normal use (EU, 2023).
- **FuelEU Maritime:** As per Directive 2023/1805 (September 2023), FuelEU Maritime does not currently allow deducting captured carbon from ships when calculating the GHG intensity. The regulation includes a provision to review new technologies by 31 December 2027, including onboard carbon capture depending on the availability of a verifiable method for monitoring and accounting of the captured carbon.

Another important regulation relevant for CCUS and transportation of CO_2 across borders is the London Protocol. Article 6 of the London Protocol prohibits transboundary export of waste, including carbon dioxide. In 2009, an amendment to Article 6 was adopted to allow transboundary export of CO_2 targeted for permanent storage under the seabed. This amendment has yet to enter into force and must be ratified by two thirds of contracting parties to do so. However, an interim solution has been agreed requiring countries to submit a declaration of provisional application and notification of any agreements to the IMO. There is some regulatory uncertainty as to how the London Protocol is managed when CO_2 is captured (and transported) across international and different territorial waters and eventually discharged for storage.

4.3.2 Safety regulations

Due to the technology's novelty in maritime, the IMO has not yet established any rules and regulations explicitly for carbon capture addressing the possible safety implications for onboard implementation. In the interim, due to interest from industry, leading Class Societies are developing guidelines and rules to ensure the safe implementation of onboard carbon capture.

DNV published guidelines for the safe installation of onboard carbon capture and storage (OCCS) in 2023 and will publish classification rules in July 2024. They cover all aspects for safe installation, including exhaust pre-treatment, absorption with the use of chemicals/amines,aftertreatment systems, liquefaction processes, CO_2 storage, and transfer systems (DNV, 2023c). These guidelines and rules must be accepted by relevant flag state administrations, and they may impose additional technical or other requirements, in order for safe implementation on ships.

4.3.3 Regulatory overview

An overview of the regulatory status is shown in Table 4-2.

TABLE 4-2

Status of environmental, GHG emission and safety regulations with regards to onboard carbon capture

		Status	Challenges and uncertainties
Environment and GHG	EEXI/EEDI & CII	Not yet included. Onboard carbon capture may be considered in future developments.	How fuel penalty is going to be included. How to take into account potential carbon capture at design stage for EEDI/EEXI. How captured emissions will be derogated for CII e.g., based on direct measurements, custody transfers, or something else.
	Future IMO regulations	IMO plans to incorporate the application of onboard carbon capture in the IMO Lifecycle Assessment (LCA) Guidelines. MEPC 81 (March 2024) discussed the issue of onboard carbon capture and established a Correspondence Group to further discuss the matter and develop a working plan on the development of a regulatory framework for the use of onboard carbon capture systems.	How onboard carbon capture will be taken into account for well-to-wake emission factors. How captured emissions will be derogated, e.g. based on direct measurements, custody transfers, or something else.
	EU MRV & EU ETS	Included.	What terms and conditions will there be with regards to carbon utilization? A verifiable method for monitoring and accounting of the captured carbon is required.
	FuelEU Maritime	No current consideration in the EU's FuelEU Maritime package. Provision for review by 31 of December 2027.	How onboard carbon capture will be included in the emission factors.
Waste Handling	London Protocol	Amendment of Article 6 of the London Protocol was proposed by contracting parties in 2009 to allow for cross-border transportation of CO_2 for sub-seabed storage. To enter into force the amendment must be ratified by two thirds of contracting parties. This is as of today pending though an interim solution has been established.	How the London Protocol is to be managed when CO_2 is captured in various territorial and international waters remains uncertain.
Safety	SOLAS	Lack of regulations and guidelines on safety and procedures.	Procedures for offloading, custody transfers, technology risk, crew training and certification of components. Comments from Flag during onboard pilot testing.
	Class	Class guidelines, rules, and notations in place.	Exploitation of pilot examples to build experience and test rules.

Abbreviations: Carbon Intensity Indicator (CII); Energy Efficiency Design Index (EEDI); Energy Efficiency Existing Ship Index (EEXI); Emissions Trading System (ETS); International Code of Safety for Ships Using Gases or Other Low Flashpoint Fuels (IGF); International Maritime Organization (IMO); The International Convention for the Prevention of Pollution from Ships (MARPOL); Marine Environment Protection Committee (MEPC); monitoring, reporting and verifying (MRV)

4.4 Practical considerations

To decide on onboard carbon capture for a particular vessel, one must consider aspects such as the effect on machinery, the evaluation of onboard carbon capture technologies, the cost benefit, and so on. In Figure 4-6, a guide for shipowners that would like to consider onboard carbon capture as an option for their fleet is provided.

Onboard modifications are required to fit the system compartments (capture, treatment, storage, consumable facilities), their casings, and their structural foundations. Figure 4-7 gives an overview of relevant parameters to consider when assessing the feasibility of onboard carbon capture technologies.

FIGURE 4-6

A three-step guide for shipowners considering onboard carbon capture (OCC)

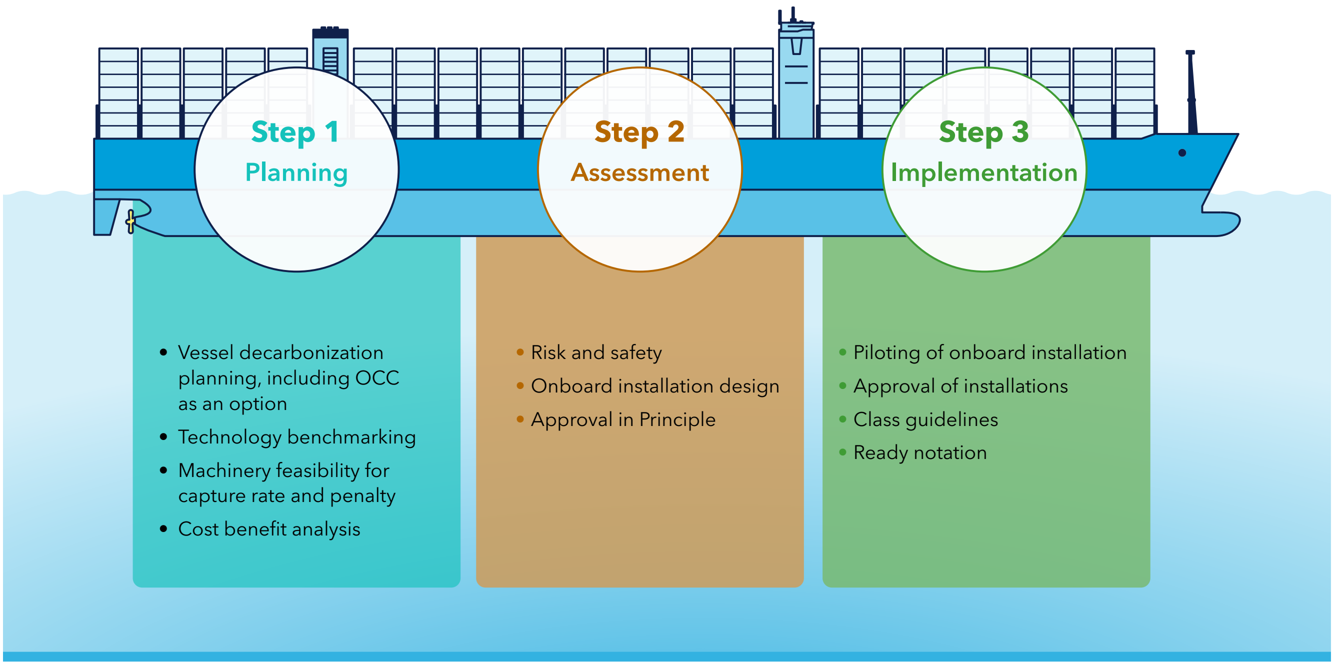
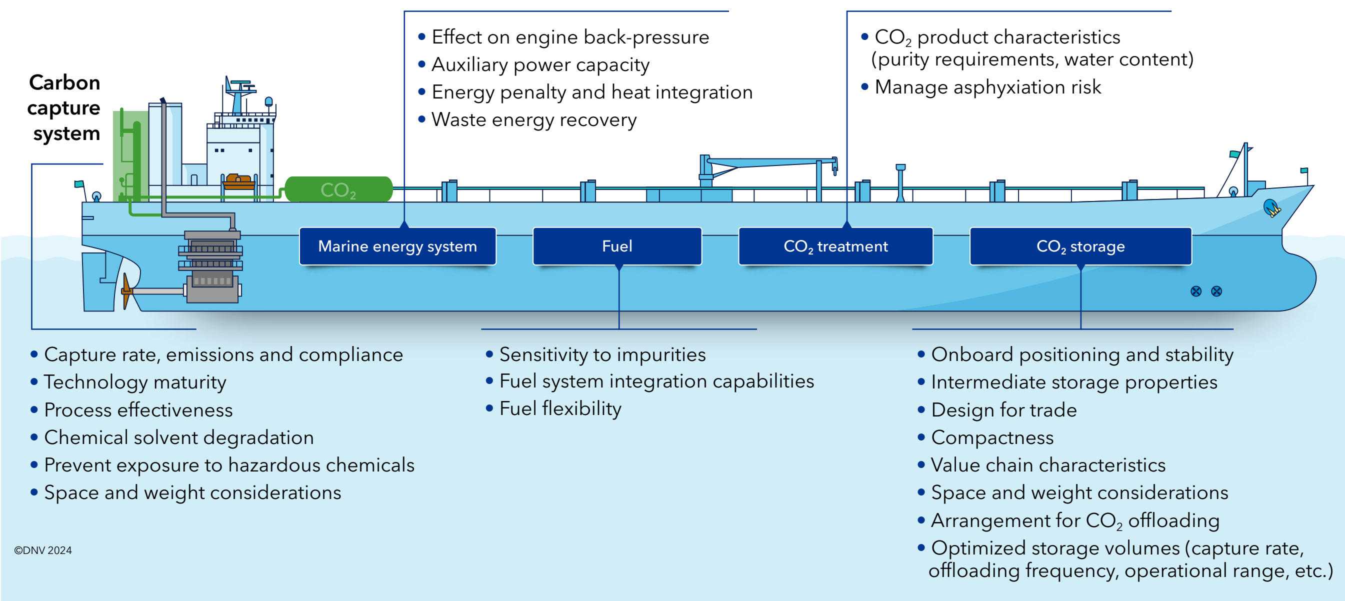


FIGURE 4-7

Key parameters worth investigating when considering onboard carbon capture



Onboard positioning

- Conventional amine-based components that implement exhaust gas scrubbing need to be placed closer to funnel casing.
- The position of the treatment plant and the storage tanks will vary with ship type as available space. For example, tankers allow for relatively easier onboard integration than other ship types, assuming the placement of CO_2 product tanks on deck.
- A CO_2 offloading system must be installed in order to dispose of the CO_2 collected onboard and connect to the wider CCUS value chain.

With the carbon capture inclusion, the design requires reassessment in terms of stability, strength, visibility and safety, to ensure, among other things, the presence of safeguards, safe passages, and maintenance routes.

Onboard arrangements will, however, differ between capture method and ship type. Figure 4-8 shows an example of practicalities (both advantages and disadvantages) for different ship types.

As there are still uncertainties related to regulations, technology and value chain developments, shipowners must investigate different decarbonization alternatives and should evaluate if onboard carbon capture could be a feasible option for their vessels. In general, an OCCS-ready[24] thinking approach could be relevant to consider at newbuilding stage to reduce cost for future potential onboard carbon capture retrofit. This means that newbuilds should be designed with the potential integration of a carbon capture system in mind, taking into account the space requirements, layout constraints, safety issues, additional energy needs, and operational impacts of different capture methods and ship types.

FIGURE 4-8

Example of practicalities related to the integration of onboard carbon capture for selected ship types

LNG carrier

+ Cooling load integration with LNG fuel

+ Less pre-treatment because of cleaner LNG fuel

+ Capacity for steam use in steam-driven ships

– Extra weight constraints capture rate

Tanker

+ Place on deck for the CO_2 tanks

+ Available heat production on board

+/– Electric power plant capacity (engines and shaft generator, if any) delimits capture capacity

– Potential cargo capacity loss / max draught

Bulk carrier

+ Low steam utilization / Available heat

+/– Bigger ships have more capacity for onboard integration. Smaller vessels have less capacities in terms of energy supply and space for tanks

– Potential cargo capacity loss / deck storage challenge. LCO_2 tank position and hatch covers opening are critical.

– Auxiliary engine capacities restrict capture rate because of liquefaction power demands

RoPax

+ Less volume because of frequent port calls. Acceptance of simultaneous operations affect business case

+/– Integration capability with locally-grown CO_2 value chains

– Less capacity for additional weight on board

! Passenger safety and accidental release of stored CO_2 is an issue. Affects location of the temporary CO_2 storage location.

Container

+ Less volume required because of frequent port calls. This benefit is expected when a global CCUS chain is fully developed.

+ Bigger vessels connecting major shipping hubs may have access to the growing CCUS value chain.

+/– Frequent port calls for smaller feeders. But possibly less timing for CO_2 offloading. Challenge tackled with simultaneous operations.

+/– Space for OCC components comes at a premium due to the potential loss of boxes. But cargo load factor may support the business case.

24) OCCS Ready – for future carbon capture and storage on board ships

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