Marine Carbon Capture Technology Review

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Acronym List

A3C .... Advanced Cryogenic Carbon Capture

ABS........ American Bureau of Shipping

AER .... Annual Efficiency Ratio

CAPEX .... Capital Expenditure

CCS........ Carbon Capture and Storage

CDV .... Carbon Descent Vehicle

CII........ Carbon Intensity Indicator

CO_2........ Carbon Dioxide

DOE .... Department of Energy

DNV........ Det Norske Veritas

EEDI........ Energy Efficiency Design Index

EEOI .... Energy Efficiency Operational Indicator

EPA .... Environmental Protection Agency

ESG........ Environmental, Social, and Governance

EEXI .... Energy Efficiency Existing Ship Index

EDS........ Energy Dispersive X-Ray Spectroscopy

FOA .... Funding Opportunity Announcement

GHG .... Greenhouse Gases

GWP........ Global Warming Potential

HAZID........ Hazard Identification

HFO .... Heavy Fuel Oil

IEEC........ International Energy Efficiency Certificate

IGC .... International Code of Safety for ships using Gases or other Low-flashpoint Fuels

IGC .... International Gas Carrier

IMO........ International Maritime Organization

ITM .... Ion Transport Membrane

IPCC........ Intergovernmental Panel on Climate Change

LCE .... Life Cycle Engineering

LNG .... Liquified Natural Gas

LR .... Lloyd's Register

MARPOL .... International Convention for the Prevention of Pollution from Ships

MCR .... Maximum Continuous Rating

MEA .... Monoethanolamine

MEPC .... Marine Environmental Protection Committee

META .... Maritime Environmental and Technical Assistance

MGO .... Marine Gas Oil

NET .... Negative Emission Technology

NOx .... Oxides of Nitrogen

OCCS .... Onboard Carbon Capture and Storage

OPEX .... Operating Expenditure

SEEMP .... Ship Energy Efficiency Management Plan

SOx .... Oxides of Sulfur

SwRI .... Southwest Research Institute

TEA .... Techno-Economic Analysis

ZEV .... Zero Emission Vehicle

Executive Summary

In 2018, the International Maritime Organization (IMO) adopted an initial strategy on reducing greenhouse gas emissions (GHG) from ships. This initial strategy aimed to reduce total annual GHG emissions from international shipping by at least 50 percent by 2050 compared to 2008 levels. The Fourth IMO GHG Study, published in 2020, reported that the total GHG emissions from marine shipping have increased between 2012 and 2018 by 9.6% to 1,076 million tonnes while the shipping emissions share has increased to 2.89% of the total, global GHG emission contribution.[1] The study concluded that while the implementation of technical measures (Energy Efficiency Design Index [EEDI]) and operational reduction measures (Carbon Intensity Indicator [CII] and Ship Energy Efficiency Management Plan [SEEMP Part III]) have been effective in reducing GHG emissions, they are not enough to meet the 50 percent target in 2050.

Most of the maritime decarbonization focus has centered on replacing traditional hydrocarbon fuels with fuels that do not contain carbon, with hydrogen and ammonia being the primary fuels of interest. To make them a reality, however, two things will be required: 1) replacement of the traditional hydrocarbon fuel logistics stream, and 2) replacement and/or modification of the equipment that is used to convert the energy contained in fuel to power vessels. This will not happen overnight, so it is logical to seek alternatives to changing that stream in order to expedite the reduction of carbon emissions in the near-term. One alternative is shipboard carbon capture and storage (CCS). While CCS cannot reduce carbon emissions to zero, it has potential to provide a significant reduction in carbon emissions until such time that zero carbon fuels and the associated infrastructure is in place. Additionally, the captured shipboard CO_2 could then be used as a feedstock for new e-fuels, creating a new global sub-economy. There is already one new shipbuilding order for a ship carrying CO_2 as a cargo, as part of the new CO_2 value chain.

This report provides an overview of the following:

- History of maritime emission reduction from the regulatory perspective, owner/operator concerns and challenges, marine technology perspective, and industry drivers
- Carbon capture and storage overview, including a review of carbon capture technologies; CO_2 storage and associated shipboard challenges; and a review of carbon packaging requirements
- Summary of marine CCS demonstration projects either completed, on-going, or being planned
- Literature review of CCS activity, research, demonstrations, etc.

Of the currently available post-combustion CCS technologies, chemical absorption or physical separation (adsorption) systems appear to have the most potential for success onboard vessels.

- Chemical absorption capture systems have the highest level of maturity and are the technology most studied for shipboard carbon capture largely because of its level of commercialization.

[1] Faber, J, Hanayama, S, et al. (2020). *Fourth IMO Greenhouse Gas Study*. International Maritime Organization. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf

Most solvents require removal of SO_2 and NOx to single digit ppm levels to avoid significant contamination of the solvent. As with all of the technologies, for chemical absorption systems it is necessary to reduce the temperature and reduce the water content of the flue gas. Capture efficiencies of 90 plus percent are easily achieved.

- Physical separation (adsorption) capture systems have an integral dehydration step which results in a dry CO_2 product. Because of the high selectivity of sorbents, no purification of the CO_2 product is required and thus the CO_2 can be directly compressed and liquefied for storage. Large-scale development of physical separation (adsorption) systems for CO_2 capture has not been completed. However, large-scale development of other commercial adsorption systems can be leveraged. Additionally, shipboard physical separation carbon capture systems will be much smaller than those envisioned for stationary power. Physical separation (adsorption) systems require a moderate amount of thermal energy and low amount of electrical power. Physical separation (adsorption) systems require a fairly complicated circuit of valves and piping for switching from adsorption to regeneration which is probably the biggest disadvantage. Capture efficiencies of 90 plus percent can be achieved.

Since chemical absorption systems are the most commercially advanced, they have received the most focus on shipboard capture studies. However, the authors believe that physical separation (adsorption) has the most potential for shipboard application at this time. A study of physical separation (adsorption) systems for comparison against the chemical absorption systems will benefit the shipping community. A follow-on techno-economic analysis should provide quantitative comparisons between technologies to further justify this conclusion. It was discovered during the literature review that there is also research and testing ongoing to determine the feasibility of capturing carbon using existing shipboard SOx scrubber units. If successful, this would provide a very near-term solution that offers a modest reduction in carbon emission.

New technology integration for marine vessels is often challenging. Some, including IMO have declared this GHG reduction activity as the "fourth revolution" of maritime propulsion. Each solution considered brings both benefits and challenges to vessel design, operations, and energy efficiency. Often solutions need to be evaluated on a case-by-case basis since there are so many variations of vessel, fleets, trade, and operation in the maritime industry today. Carbon capture and storage as a GHG solution is no different. In short, CCS will work better for some vessels and not others. There are space, power, and weight requirements that must be considered as well as the logistics of offloading CO_2 in ports along a vessel's trade route. Overall CCS has been determined to be technically feasible and provides a quick win opportunity for near-term GHG emission reduction. The LCE team recommends the following future work:

- Host a seminar to discuss the shipboard carbon capture space.
- Techno-economic analysis study –evaluate both an ocean-going and an inland waterway vessel on available data and vendor capture data.
- Create carbon capture database of vendors, projects, and operators.
- Demonstrate CCS System on a vessel – recommend either a harbor vessel or inland waterways towboat.

1 Background Discussion

In 2018, the International Maritime Organization (IMO) adopted an initial strategy for reducing greenhouse gas emissions (GHG) from ships.[2] This initial strategy aimed to reduce total annual GHG emissions from international shipping by at least 50 percent by 2050 compared to 2008 levels. As IMO's Marine Environmental Protection Committee (MEPC) continues to develop and implement changes to Annex VI of the International Convention for the Prevention of Pollution by Ships (MARPOL Annex VI), there are calls by various world governmental bodies to accelerate the process.[3]

In June 2022, the MEPC held their 78th Session to review and strengthen the initial IMO strategy on reduction of GHG emission from shipping and to develop a "basket" of GHG reduction measures.[4] The proposed new measures would require all ships to 1) calculate their Energy Efficiency Existing Ship Index (EEXI) following technical methods to improve their energy efficiency, and 2) establish their annual operational Carbon Intensity Indicator (CII) and CII rating. This rating links CO_2 emissions to the amount of cargo carried and the distance traveled. Further work is planned to revise the initial GHG emission reduction strategy.

The U.S. Government, under the Biden Administration, has been clear in its commitment to work with IMO more aggressively to achieve GHG emission reductions. In April 2021, Special Presidential Envoy for Climate, John Kerry, announced that the U.S. was committing to work with IMO to adopt a goal of reaching zero emissions from international shipping by 2050.[5] This aligns the U.S. with many other IMO Member States.

On April 15, 2021, the U.S. Congress held a Coast Guard and Maritime Transportation Subcommittee hearing on decarbonization of the maritime industry.[6] Congress recognized how difficult and complex the decarbonization issue will be for the maritime industry, and several key elements were identified during the hearing. These included the cost of new standard compliance, U.S. participation in international regulation setting, federal investment requirements in ports and shoreside infrastructure, and assessing and investing in research and development of alternative fuel technologies.

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[2] *Initial IMO Strategy on Reduction of GHG Emissions From Ships.* (2018). https://wwwcdn.imo.org/. https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.304(72).pdf

[3] *U.S. Poised to Urge the International Maritime Organization to Dramatically Accelerate Decarbonization of Shipping*. (2022). The National Law Review. https://www.natlawreview.com/article/us-poised-to-urge-international-maritime-organization-to-dramatically-accelerate

[4] *Cutting ships' GHG emissions - working towards revised strategy*. (2022). International Maritime Organization. https://www.imo.org/en/MediaCentre/PressBriefings/pages/MEPC-78-.aspx

[5] *US Climate Envoy John Kerry Calls for 2050 Zero Emissions Target at IMO*. (2021). Ship & Bunker. https://shipandbunker.com/news/am/794256-us-climate-envoy-john-kerry-calls-for-2050-zero-emissions-target-at-imo

[6] *Congress Set to Discuss Maritime Decarbonization*. (2021). The National Law Review. https://www.natlawreview.com/article/congress-set-to-discuss-maritime-decarbonization

Most of the maritime decarbonization focus has centered on replacing hydrocarbon fuels with fuels that do not contain carbon, with hydrogen and ammonia being the primary fuels of interest. To make them a reality, however, two things will be required: 1) replacement of the traditional hydrocarbon fuel logistics stream, and 2) replacement and/or modification of the equipment that is used to convert the energy contained in fuel to power vessels. The logistics stream includes the fuel production, delivery, and storage aspects both onshore and afloat. Over the past 11 years, LCE has supported the U.S. Navy's alternative fuel qualification program. One of their initial principles for the insertion of non-petroleum derived alternative fuels was that it had to be fungible, so the current logistics stream would not require any modifications. The costs and program risks for conversion of this part of the fuel system were both daunting and beyond the Navy's direct control. Therefore, by clearly making this a requirement, the Navy could focus the testing and qualification specifically on how these alternative fuels work in both legacy and future propulsion and power generation equipment.

In following this philosophy for the decarbonization pathway, it is logical to seek alternatives to changing that stream in order to expedite the reduction of carbon emissions in the near-term. Of course, the biggest problem for a ship owner is that they can only control the onboard fuel storage and energy conversion equipment part of the decarbonization process. They need to rely on the rest of the fuel supply industry to develop shoreside production, distribution, and storage systems first. Onboard carbon capture and storage would provide a measure to reduce carbon emissions now without waiting for the rest of the fuel distribution system conversion to occur.

The Department of Energy (DOE) has been working on the Carbon Capture and Storage (CCS) program since 1997 in the Office of Fossil Energy. With recent funding from Congress, including $3.5 billion from the bipartisan Infrastructure Law, the DOE is funding a variety of projects. The programs include direct air carbon capture; natural gas, power, and industrial sector carbon capture and sequestration; and carbon utilization projects. [7] Their emphasis is on research, technology development, and demonstration.

Internationally, there are some mobile source projects under development, although most of the work remains focused on stationary, large CO_2 emitters. One notable mobile source project was conducted by Mitsubishi Shipbuilding. In 2020, they embarked on testing the world's first marine-based CO_2 Capture System in partnership with K Line and Class NK. Their plan is to demonstrate a CO_2 capture system on a K Line coal carrier.[8] The program aim was to convert a CO_2 capture system designed for onshore power plants and adapt it to an in-service ship. Their project is called "Carbon Capture on the Ocean" or simply CC-Ocean. There are also many other studies and demonstration projects for marine carbon capture and storage. These are discussed in Sections 2 and 3 of this report.

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[7] *Biden Administration Launches $3.5 Billion Program To Capture Carbon Pollution From The Air*. (2022). Energy.Gov. https://www.energy.gov/articles/biden-administration-launches-35-billion-program-capture-carbon-pollution-air-0

[8] *Mitsubishi Shipbuilding to Test World's First Marine-based CO_2 Capture System-- "CC-Ocean" Project in Partnership with "K" Line and ClassNK Part of Japan Government Initiative to Support Development of Marine Resource Technologies*. (2020). Mitsubishi Heavy Industries, Ltd. https://www.mhi.com/news/20083101.html

Marine CCS activity is in concert with the last element of the Congressional hearing. Alternative fuel technologies such as hydrogen and ammonia, as well as wind and electric vessels, are all part of the solution set proposed for an envisioned zero emissions future. Instead of making the daunting investment to change the entire fuel logistics infrastructure and shipboard storage and propulsion equipment, it is possible to consider the use of after-engine exhaust carbon capture technology to achieve nearly the same results. This report evaluates the opportunities and technologies available for onboard carbon capture and storage as an alternate methodology to decarbonizing marine vessels to meet the IMO goals for 2050 GHG reduction and reduced ship carbon intensity.

1.1 Definitions/Concepts

It is essential to define a few basic terms, which are intended to be in concert with the Intergovernmental Panel on Climate Change (IPCC). The terms have evolved and continue to be refined as they are studied and better understood. In 2007, the IPCC published a study that is used as the basis for many of the definitions below. [9]

Annual Efficiency Ratio (AER) – IMO index used to measure the CO_2 emissions of the fleet by its cargo carrying capacity in deadweight tons regardless of load condition. (gCO_2/dwt-nm).

Capture Rate – how much CO_2 is collected from emissions during the CCS process. Different technologies have different capture rates.

Carbon Capture and Storage (CCS) – the process of trapping the CO_2 produced by a process and storing it in such a way that it has no impact on the atmosphere.

Carbon Circulation – the process of applying a sustainable carbon cycle. Concept designs like HyMethShip™ capture the CO_2, store it, and return it to processing plants to produce a hydrocarbon fuel that is then reused by the ship.

Carbon Dioxide-Equivalent Emissions and Concentrations – the number of metric tons of CO_2 emissions with the same global warming potential as one metric ton of another greenhouse gas. Methane, for example, is cited as being 29.8 times more potent than CO_2.[10] This is one of the issues with using natural gas, because leakage or methane slip will produce 29.8 times more emissions impact than the same amount of CO_2 emissions.

Carbon Footprint – the amount of CO_2 and other carbon compounds emitted by a particular process, vessel, group, etc.

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[9] *IPCC, 2007: Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

[10] *Climate Change 2021: The Physical Science Basis*. (2021). International Maritime Organization Intergovernmental Panel on Climate Change Working Group I.

Carbon Intensity – measure of CO_2 emitted per metric ton of cargo and per distance (km). IMO has targeted a reduction in carbon intensity for international shipping of at least 40% in 2030 and 70% by 2050 as compared to 2008 levels. EEOI and AER indexes are used for these comparisons.

Carbon Intensity Indicator (CII) – The CII measures how efficiently a ship transports goods or passengers and is given in grams of CO_2 emitted per cargo-carrying capacity and nautical mile. In November 2022, this mandatory IMO measure will come into force per MARPOL Annex VI for all cargo, cruise, and RoPax vessels above 5,000 gross tonnes. This methodology establishes a graded evaluation system of A through E, with three consecutive years of D (or one year of E) grades requiring corrective action plans.

Decarbonize Shipping – Term used to define reducing the GHG emissions from marine vessels.

Energy Efficiency Design Index (EEDI) – The EEDI is a carbon design/technical efficiency indicator that provides a specific figure for an individual ship design, expressed in grams of CO_2 per ship's capacity-mile (the smaller the EEDI, the more energy efficient the ship design). The EEDI is calculated by a formula based on the technical design parameters for a given ship and only applies to new ships.

Energy Efficiency Existing Ship Index (EEXI) – The EEXI is a carbon design/technical efficiency indicator which is applicable to most in-service vessels over 400 gross tonnes (GT) that operate internationally. It is similar to its predecessor, the Energy Efficient Design Index (EEDI), but applies to existing ships outside of EEDI regulations. Emissions are described per cargo tonne and mile. The EEXI is scheduled to come into force on 1 January 2023.

Energy Efficiency Operational Indicator (EEOI) – An IMO index used to measure actual operating carbon intensity of a fleet of vessels by using CO_2 emitted to transport 1 tonne of cargo 1 nautical mile (gCO_2/t-nm)

GHG Footprint – term that represents the amount of CO_2 plus other GHGs (converted into CO_2-equivalency terms) emitted by a particular process, vessel, group, etc.

Global Warming Potential (GWP) – a measure of how much energy the emissions of one ton of a gas will absorb over a given period of time, relative to the emissions of one ton of carbon dioxide. Each GHG has a different warming influence and lifetime in the atmosphere and therefore a different impact.

Greenhouse Gas (GHG) – natural and anthropogenic (originating from human activity) gaseous pollution that can absorb infrared radiation and trap heat in the atmosphere. These include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and hydrofluorocarbons (HFCs).

IMO GHG Emission Reduction Strategy – IMO plan to reduce marine GHG emissions along with methane slip from natural gas-fueled equipment. All requirements and reduction targets are based on a 2008 baseline, measured as 794 million tonnes of CO_2, per the IMO 4th GHG Study in 2020.

International Energy Efficiency Certificate (IEEC) – Since 2013, vessels above 400 GT falling under MARPOL Annex VI have been required to hold onboard a ship-specific energy efficiency management plan, that was reviewed and that for which an International Energy Efficiency (IEE) certificate was issued on a one-time basis.

Marine Carbon Emissions – Carbon emissions associated with marine vessels. According to the Fourth IMO GHG Study in 2020, an estimated 1,056 million tonnes of CO_2 was emitted in 2018 by international shipping which accounts for 2.89% of the total CO_2 emissions worldwide.[1]

Negative Emissions Technology (NET) – Term used to describe removing CO_2 from the environment through direct air capture and/or improving the carbon cycle capture. For example, the combination of bio-derived fuels and CCS provides a NET opportunity since the CO_2 is captured and stored, preventing it from affecting the atmosphere.

Net Zero Carbon Fuels – Any carbon fuels (other than H_2 and NH_3) where GHG emissions are theoretically zero when measured over the life cycle (from extraction/cultivation to exhaust stack). Net zero carbon fuels achieve a balance between the carbon emitted into the atmosphere and the carbon removed from it.

Net Zero Carbon Emissions – Achieving a balance between the carbon emitted into the atmosphere and the carbon removed from it.

Purity – Defined as being free from contamination. The purity of carbon captured during the CCS process can have effects on how the carbon is stored and handled.

Renewable Fuels – Fuels made from sustainable biomass and renewable electricity.

Ship Energy Efficiency Management Plan (SEEMP) – The SEEMP is a management requirement that established a mechanism to improve a ship's energy efficiency. It provides a mechanism to manage ship efficiency over time using the Energy Efficiency Operational Indicator (EEOI) as a monitoring tool.

Triple Point – The temperature and pressure at which the three phases (solid, liquid and gas) of a substance coexist in thermodynamic equilibrium.

Zero Carbon Fuels – Includes non-carbon containing fuels, such as ammonia and hydrogen.

Zero Emissions – Defined as zero carbon emissions from a given activity, meaning no carbon is produced by that activity. For example, using non-carbon fuels like hydrogen or ammonia to produce power will yield zero CO_2 emissions and therefore have zero (carbon) emissions.

Zero Life Cycle Emissions – Defined as zero carbon emissions from the entire fuel life cycle – from extraction/cultivation to exhaust stack.

1.2 Historical Context

Any technology review requires an understanding of the historical context upon which the review is built. For this project, the historical context includes: the evolution of the maritime regulatory requirements, owner/operator challenges, marine technology and innovation, and industry drivers associated with making significant and unprecedented changes so quickly. Considering the different shapes, sizes, and purposes of marine vessels, it becomes apparent that one solution will not fit all applications. This section describes the perspectives that form the framework for reduction of maritime GHG emissions. It also evaluates these perspectives to understand why maritime GHG emission reduction is so complicated and has so many different facets to consider.

1.2.1 Regulatory Perspective

Marine exhaust gas emissions and their regulation and control is not a new element to the maritime industry. In 1973, IMO published a set of ship pollution rules known as MARPOL. These rules were amended in 1978. However, these regulations did not cover marine exhaust gas emissions. It wasn't until 1997 that Annex VI was published and finally covered a subset of marine exhaust gas emissions, namely NOx and SOx emissions. MARPOL Annex VI was ratified by member states in 2005 and specifically applied to new internal combustion engines with brake power greater than 130 kW installed on vessels on or after January 1, 2000, or vessels that were re-powered during a major conversion. This was about the same time that the Tier system was established in the United States by the Environmental Protection Agency (EPA).[11] Tier 1 emission standards for new nonroad (or off-road) diesel engines were adopted in 1994. These regulations led engine manufacturers to develop lower emission designs to ensure ship operators would be compliant with the requirements.

In 2008, additional amendments were enacted that introduced, for the first time, fuel quality requirements. New Tier II and Tier III emission standards focused on NOx, particulate matter, and CO_2, as well as application of Tier I requirements on pre-2000 engines, was also enacted. More importantly, this amendment also introduced a dual set of fuel requirements – one for global use and one that was more stringent for vessels operating in a sensitive environmental area known as an Emission Control Area (ECA). For example, a North American ECA was adopted to include most of the US and Canadian coasts and required lower sulfur fuels to be used when operating in these regions to reduce SOx emissions.

It was not until 2011 that amendments to Annex VI were introduced to "reduce emission of greenhouse gases (GHG)". Specifically, Chapter 4 added regulations for energy efficiency of ships, which in turn reduced fuel consumption, thereby reducing GHG emissions. Two mandatory elements were added to ensure ship energy efficiency standards – the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). These became effective in 2013 with some opportunity to measure the effectiveness of best practices and fleet and ship performance improvements through the use of EEOIs. Per IMO, this marked the first legally binding climate change treaty to be adopted since the Kyoto Protocol.[12]

In 2018, IMO adopted an initial GHG emission reduction strategy to reduce GHG emissions from international shipping with the goal of phasing them out as soon as possible. The strategy was based on the following three pillars:

1. Reducing carbon intensity (CO_2 per transport work [gCO_2/tonne-nautical mile]) by at least 40% by 2030 and working towards 70% by 2050, using 2008 as the baseline.
2. Reducing total annual GHG emissions by at least 50% by 2050, compared to 2008.

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[11] *US: Nonroad: Emissions*. (n.d.). TransportPolicy.Net. https://www.transportpolicy.net/standard/us-nonroad-emissions/

[12] *Energy Efficiency Measures*. (2020). International Maritime Organization. https://www.imo.org/en/OurWork/Environment/Pages/Technical-and-Operational-Measures.aspx

3. Reducing the carbon intensity of ships through implementation of further phases of the energy efficiency design index (EEDI) for new ships.

These goals were established to be in concert with the Paris Climate Agreement temperature goals.[2]

Subsequent meetings of the IMO's Marine Environmental Protection Committee (MEPC) have led to the most recent MEPC 78 in June 2022.[4] Several notable results related to energy efficiency and CO_2 emissions were adopted. These included implementing EEXI and CII ratings and an enhanced SEEMP. These will provide evaluations of the carbon intensity of marine vessels above 5,000 Gross Tons. IMO's MEPC also designated the entire Mediterranean Sea as an ECA for SO_2. If adopted at MEPC 79, the regulations would enter into force in mid-2024 and take effect in 2025.

1.2.2 Owner/Operator Perspective

At any given time, owner/operators have vessels being retired for scrap or sale, operating, under design, or in planning. The design cycle and life varies depending on the vessel type, operating profile, and location of operations. However, one common thread exists – when a regulatory decision is made, evaluation of the vessel's life cycle must be considered. This is especially true in the case of IMO's GHG reduction goal of 50% reduction by 2050. That's only 28 years to accomplish these goals. Vessels operating on the U.S. inland waterways and Great Lakes typically have an average vessel life of 35+ years so any ship being delivered today will most likely be operating in 2050. Therefore, the methodologies and technologies being developed today to reduce GHG emissions need to not only work for new-design ships but also be able to be retrofitted into existing ships that will still be in service in 2050.

This scenario poses a daunting challenge to owner/operators who want to do the right thing but are also in business to make a profit and keep their fleets operating and growing. At the same time, the regulations, guidance, and technologies keep evolving and shifting as more is learned and studied. Several key questions always come up as new technologies are being considered, such as:

- What is the impact to operations (bunkering, crew training, costs, cargo revenue, ship stability, etc.)?
- What is the right technology choice (renewable fuels, low- and zero-carbon fuels, alternative propulsion technology, after-exhaust capture, etc.)?
- Will additional infrastructure be required to support the vessel changes in fuel or emission reduction technology? (non-traditional fuel bunkering, shore-power, shoreside handling and disposal of working fluids for exhaust scrubbing, etc.)?
- Is there the option for owner/operators to switch back if the technology does not work? (agreement in principle for ships designed for ammonia, methanol, dual fuel engines – natural gas/fuel oil, engine manufacturers design of multifuel engines – requiring conversion kits for different fuels, etc.)?
- Is financing available for the additional capital expenditure requirement?

These are only a few of the questions that are frequently discussed at board meetings, staff meetings, and in other forums. For example, examining the recent ship owner tactical decisions relating to meeting SOx Emissions Control Area (ECA) requirements shows the complications associated with meeting emission requirements using traditional marine equipment. Two major pathways were offered by regulators and chosen by owner/operators – fuel switching and SOx exhaust gas capture. Both required modifications to shoreside infrastructure, shipboard infrastructure, and ship operations as well as significant costs. What made this activity complex is the fact that at any given point in time, there were vessels already in service, vessels under construction, and vessels that were still being considered or under design negotiations. To add to the complexity, there are a large variety of vessel sizes, shapes, trade routes or operations and cargoes so one solution was not going to fit every vessel. Segueing to a similar emergent requirement, GHG emissions, it is logical to consider the same alternatives.

As part of the fuel switching activities to support reduced SOx emissions, there was already some momentum for conversion of vessels to use natural gas as a fuel. Natural gas typically yields a cleaner combustion and eliminates SOx emissions. The conversion requires new shoreside and bunkering logistics and equipment, different fuel tanks, different handling for shipboard storage and supply, and engine modifications or engine re-powers to make use of natural gas as a marine fuel. When considering natural gas, one of the concerns often mentioned is methane slip, which is un-combusted natural gas that makes its way into the engine exhaust gas stream. While burning natural gas solves the SOx problem, it turns out that methane is 29.8 times more potent in the atmosphere than the same volume of CO_2. Unintended consequences, such as this, are only one of the many concerns that owner/operators must contemplate when deciding on a technology to meet new regulations.

1.2.3 Marine Technology Perspective

From a marine technology perspective, the GHG reduction business has exploded. Classification Societies like American Bureau of Shipping (ABS), Det Norske Veritas (DNV), and Lloyds Register (LR) are all involved and keeping ahead of the curve by not only providing tools for keeping score but also helping educate and develop approaches, philosophies, and technologies. They have also adapted a process to agree in principle about conversion of vessels at some later date to another fuel during the design and construction process. This will provide owner/operators the ability to change to a lower GHG fuel when it becomes commercially and economically available.

Equipment manufacturers, engine builders, and energy companies are all participating to varying degrees to progress technology, make equipment and ships fuel-flexible, and improve the availability of renewable and sustainable hydrocarbon fuels as well as beginning the process of developing production and infrastructure for supply of non-hydrocarbon alternate fuels. For example, when ARAMCO recognized a few years ago that there was need for GHG reduction, they began to develop mobile carbon capture technology for use on automobiles, trucks, and marine vessels.

Governmental bodies, research institutes, and traditional marine consulting firms are all stepping up to transition existing shoreside technologies, develop and test equipment and engines, and fund research and development. For example, U.S. DOE has been working in the carbon capture and sequestration space for over 25 years. The U.S. DOE has been engaged with MARAD's Maritime Environmental and Technical Assistance (META) program for many years to continue to demonstrate technologies like fuel cells, sustainable biofuels, and carbon capture aboard vessels, in real-world applications. Southwest

Research Institute (SwRI) has ongoing test programs for hydrogen and ammonia combustion and have developed their own LNG engine conversion kits.

There is plenty of activity surrounding the marine GHG reduction technology perspective with almost daily announcements of companies making decisions to use methanol, hydrogen, or all-electric propulsion. What is clear is that all of these groups must work together because no single solution will work for all vessel types. Establishing a clearinghouse for GHG-reducing technologies, fuels, and requirements is essential because the maritime industry is often in a quandary with what to choose. As these rapidly evolving activities occur, the need for understanding what is real, what works, what complies with regulations, and what the costs are becomes critical. MARAD is stepping up to help the U.S Maritime Industry by working with operators, regulators, and vendors around the world to provide clear information that will aid in making these decisions.

1.2.4 Industry Driver Perspective

Many drivers influence the need for exhaust gas emission reductions and more specifically GHG emissions. As diverse as the maritime industry is in vessels, trades, and operations, these drivers influence owner/operators in different ways and with varying impact. Activity like the developing IMO requirements drive ocean-going fleets much more than domestic or inland fleets. As an example, the impact of the North American ECA created a requirement for ocean-going operators to bunker two fuels so they could switch fuels when entering the ECA, while U.S. inland operators were not impacted at all since they had already transitioned to low sulfur fuel per a mandate by the U.S. EPA. Even the IMO recently released IMO requirements for CII and EEXI impact vessels of different tonnage and exclude those below a certain tonnage for now.

Capital costs and revenues traditionally influence the decisions on how to meet requirements. As the worldwide push for global greenhouse gas reduction has gained momentum, so has the ability to access capital and investors to help make fleets “greener”. Additionally, the proposed carbon tax on fuel that IMO is discussing assures an equal playing field and might reduce the cost differential for GHG reduction technology and accelerate funding for retrofit or new designs to meet IMO goals. Decisions to retrofit, or break and build, will be made as owner/operators work to reach the GHG reduction goals – these are helped along if funding or other incentives are available. This also applies to the accompanying infrastructure to support renewable fuel production, new low- or zero-carbon fuels, new cleaner energy conversion devices, and carbon sequestration.

Another driver that is emerging as a powerful motivator is the cargo owners and consumers who have become vocal in their demand for products with smaller carbon footprints. Large corporations, investors, and consumers are all more aware of their impact to the environment. New terms like “sustainability” and “life cycle analysis” are making their way into the public’s lexicon. Additionally, corporations, including the shipping companies themselves, are under more pressure to publicly state their environmental, social, and governance (ESG) goals. Even privately held companies are being asked for their products’ carbon footprint or product life cycle analyses. All of this is creating a rather recent, yet strong, push to drive maritime decarbonization. For example, those transporting goods for companies, such as Amazon and Ikea, are driven heavily by their customers’ policies relating to net zero or reduced GHG emissions. Many individual companies are joining a climate pledge to reach net zero emission by 2040 – this includes their own energy use as well as all suppliers and those transporting their products.

1.2.5 Many Options – It is Complicated

The maritime industry is complex, typically operating on both fresh and seawater and carrying cargo, passengers, or offshore rig supply/support. New vessel applications are also emerging, such as offshore wind farm support vessels and even newly discussed CO_2 carriers. Their operational profile, distances travelled, and design are manifold. While many vessels are covered by IMO regulations, many more are not since they may not participate in international shipping or are of a size under regulation. What is clear, however, is that all will be facing new requirements and scrutiny, as new marine fuels emerge and current ones potentially disappear or cost more.

While IMO, ship operators, and governments are working to reduce GHG emissions, so are other industries. The quests are similar, as are the solutions. One of the biggest concerns is that each of these industries is counting on the "blue" solutions (i.e. renewable energy sources) to solve their specific problems. The International Chamber of Shipping published a report that reviewed the opportunities and challenges associated with what they term the "fourth propulsion revolution".[13] Throughout the report, it is made very clear that although the maritime industry is only responsible for a small part of the global GHG emissions, it should be given priority of government and industry (including the energy industry) support to increase the transition to green fuels since it is likely that the industry will play a major role in transporting green fuels for other industries throughout the world. The report also points out that green fuel production will rely heavily on electricity from renewable sources – those same sources that the other ~97 percent of GHG producers also plan on using. They projected that for shipping to meet the net zero carbon target, 3,000 TWh of electrical power from renewable sources will be required, which is equivalent to all of the world's current renewable power generation. They also state that to meet IEA's net zero emissions by 2050, an 18-fold increase in the world's existing renewable production capacity is required, with the maritime industry needing 1/18th of this power. Given the sheer magnitude of these requirements, it is logical to consider a combination of technologies, including carbon capture and storage, to meet the need.

With regard to marine exhaust gas emissions – it is simple in conceptual terms, yet complex to implement. IMO, through their MEPC, have been doing a marvelous job increasing the efficiency of current and future vessels through use of the Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP). These have helped to reduce both fuel consumption and marine exhaust gas emissions. The establishment of Emission Control Areas (ECAs) has further pushed the industry to change operational strategies and modify equipment. These have driven dramatic change already.

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[13] *Fuelling the Fourth Propulsion Revolution*. (2022). International Chamber of Shipping. https://www.ics-shipping.org/publication/fuelling-the-fourth-propulsion-revolution-summary-report/

Up until now, most of the conversations have been about improving current technology, along with some minor fuel changes. With GHG emissions, the conversations have changed dramatically and swiftly. Talk of switching to lower sulfur fuels to operate in ECA areas used to cause angst with owner/operators – now talk of using fuels like hydrogen, ammonia, methanol rather than conventional or alternate non-petroleum derived fuels are emerging. Hydrogen and ammonia are both non-carbon fuels, so they would produce zero CO_2 emissions if they can be combusted to provide power. However, the least expensive way to currently produce these fuels is through natural gas reformation. Therefore, to be truly green, renewable energy sources like hydropower, wind, or solar would have to be used to replace current processes in order to achieve near-zero emissions throughout the entire lifecycle process. Current natural gas production could only be used if carbon capture is added to the back end; otherwise GHGs are generated and emitted which defeats the purpose of using these fuels. Methanol is another fuel under consideration, primarily because it can be produced and easily reduced to hydrogen on demand. It can also be produced using renewable energy from captured CO_2 and hydrogen from electrolysis, resulting in what is termed green methanol. Currently, none of these fuels are produced at a large enough scale or by using GHG-friendly processes.

Words like carbon neutral, zero GHG emissions, net zero emissions, and negative emissions technologies are entering the lexicon of operators, regulators, and governments alike. Large industry leaders like Maersk have announced that they are building a fleet of ships operating "carbon neutral" methanol. Worldwide engine makers like Caterpillar, MAN, and Wartsila have announced programs to test methanol, hydrogen, and ammonia.

The pace of these initiatives feels frenetic. There is a lot of work to do between now and 2050. When you consider that coal-fired vessels were still operational in the inland waterways until the 1950's, to meet these aggressive GHG goals in 28 years will most certainly require more than one solution.

Carbon capture must be considered a part of the solution set chosen by owner/operators. According to ABS, "*Carbon capture is going to be a key transformational technology for shipping to achieve net zero emissions by 2050. It will be critical to addressing the challenge before us, which is the sheer gradient of the curve. At the moment we can only see the outline of a solution to get us to 2050. But it is clear already that net zero cannot realistically be delivered without efficient carbon capture and storage technology*."[14] In concert, ABS published a report on their "Zero Carbon Outlook" which discusses and introduces two emergent value chains – hydrogen and carbon.[15]

1.3 Marine Carbon Capture and Storage

1.3.1 Why Carbon Capture and Storage

The most often discussed solution for decarbonizing marine vessels is sustainable, and in some cases non-hydrocarbon, fuels such as hydrogen and ammonia. However, unless the sustainable fuel is a drop-

[14] Howard, G. (2022). *Carbon capture key to net-zero by 2050*. Seatrade Maritime News. https://www.seatrade-maritime.com/sustainability-green-technology/carbon-capture-key-net-zero-2050

[15] American Bureau of Shipping. (2022). *Setting the Course to Low Carbon Shipping - Zero Carbon Outlook*. https://maritimecyprus.com/wp-content/uploads/2022/06/ABS-Sustainability-outlook-2022_06.pdf

in replacement for current fuels and fungible with current fuels, there is a significant amount of work to be done shoreside and on the vessels to accommodate these new fuels.

While this report will not detail the future of zero carbon fuels, it is very important to understand the current status and progress of those fuels. In 2021, the World Bank published a report, "The Potential of Zero Carbon Bunker Fuels in Developing Countries".[16] Since hydrogen and ammonia are not naturally occurring, they need to be produced. As previously discussed, the most cost-efficient method of production for hydrogen and ammonia is currently natural gas. Figure 1 shows the World Bank's perspective on how to produce zero carbon bunker fuels.[16] Note they make a distinction between blue and green fuels. Blue fuels are those that are produced from more traditional methods using natural gas with carbon capture and storage on the back end while green fuels use renewable power to produce the fuels. Currently, almost all of the hydrogen, ammonia, and methanol production in the world is used to support other industrial processes and the chemical industry. To scale up their production to supply the marine industry with replacement fuels will require significant investment in both capital equipment and renewable energy sources. Similar discussions and evaluations are underway for renewable or synthetic natural gas production to replace current shipboard natural gas where possible. This only covers the fuel production element.

To establish and support hydrogen as a maritime fuel, as shown in Figure 2, both a shoreside infrastructure (fuel production, transport, and storage) and shipboard infrastructure (onboard storage, fuel service and supply, energy conversion, and exhaust) need significant development. All of these pieces are under research and development by U.S. DOE, private industry, and many worldwide. Hydrogen, ammonia and methanol roadmaps are emerging to support these activities.

[16] "Englert, Dominik; Losos, Andrew; Raucci, Carlo; Smith, Tristan. 2021. *The Potential of Zero-Carbon Bunker Fuels in Developing Countries*. World Bank, Washington, DC. © World Bank. https://openknowledge.worldbank.org/handle/10986/35435. License: CC BY 3.0 IGO.

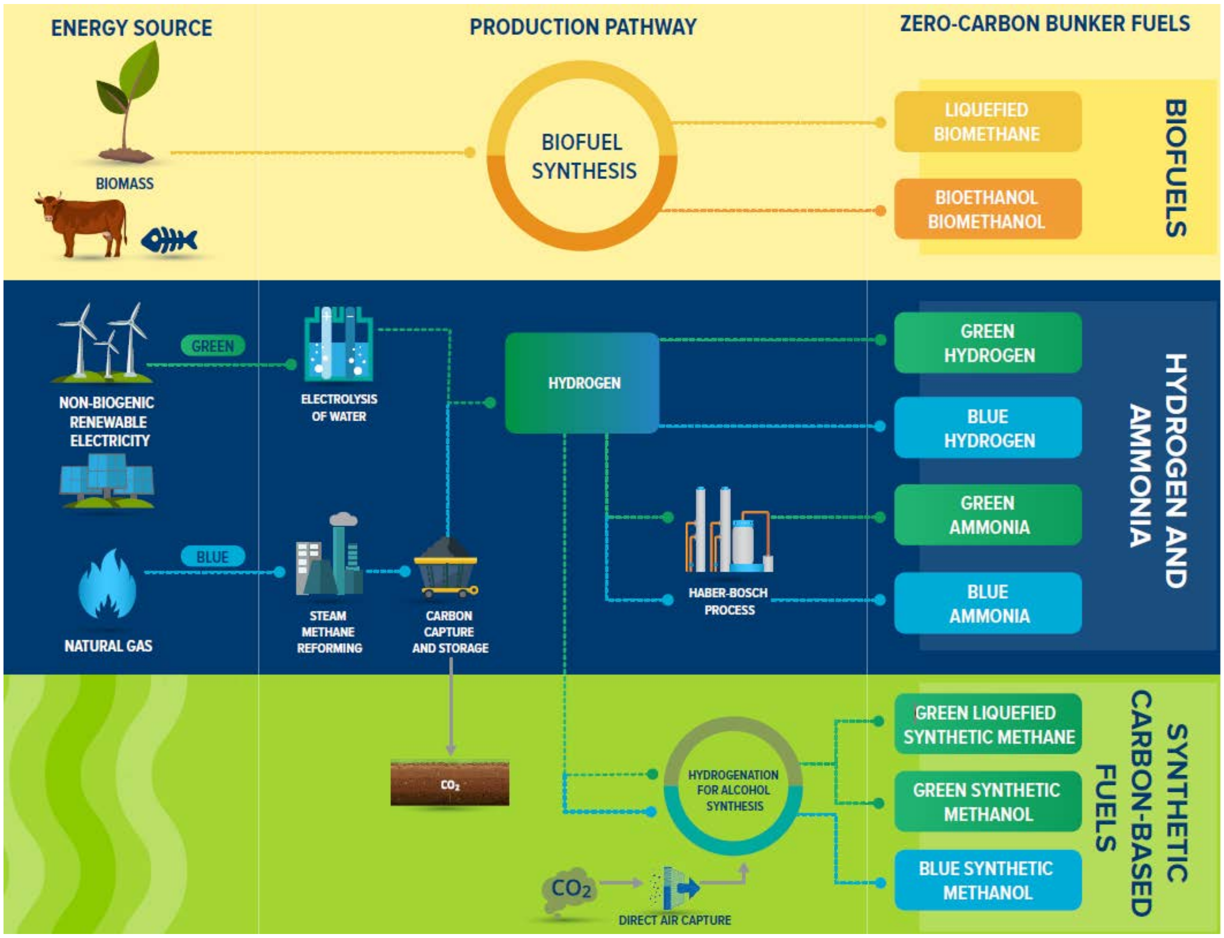

Figure 1. World Banks Future Zero Carbon Bunker Fuel Production Pathways

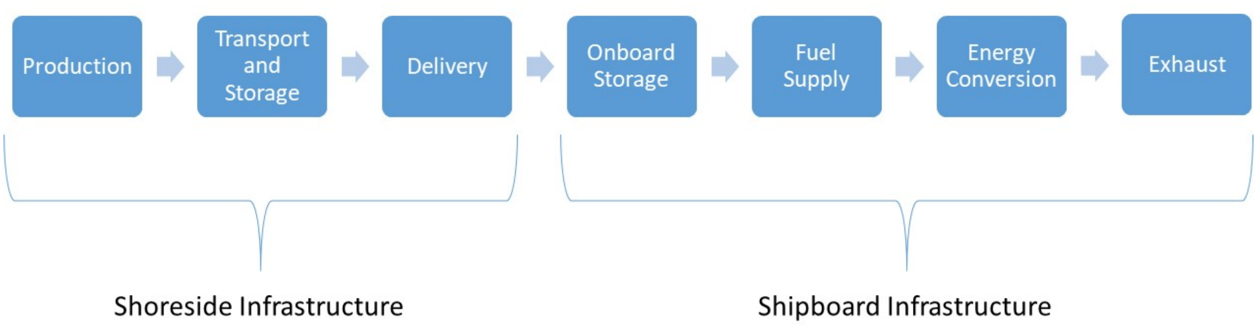

Figure 2. Requirements for Hydrogen Conversion of Vessels

The maritime industry's focus is on developing strategies and technologies to convert the current hydrocarbon fuel shipboard infrastructure to a radically different fuel. Their focus is on onboard storage, fuel supply, energy conversion equipment, and exhaust systems as shown on Figure 3. Vessel fuel system design, engine room spaces, ventilation systems, and fire safety systems need to be redesigned to ensure that any new fuel is as safe as current marine fuels

This work has already begun as natural gas has made its way aboard some non-LNG carrier vessels worldwide. Currently, natural gas is transported, stored, and used onboard as liquefied natural gas (LNG) which is cryogenically stored at -260°F. Just like LNG, hydrogen will likely be stored as a liquid cryogenically at -423°F. For both of these fuels, the volumetric energy density is greatest as a liquid, which drives the requirement for cryogenic tanks.

IMO has adopted an international safety code for ships using gases and other low flashpoint (below 60°C) fuels. This document, known as the IGF (International Code of Safety for ships using Gases or other Low-flashpoint Fuels), was written to cover those ships that use these fuels as opposed to those ships carrying LNG as cargo (which are covered by an older, and similar IGC (International Gas Carrier) Code).[17]

The IGF code governs design considerations and regulations for making sure that machinery and spaces are gas-safe. Figure 3 identifies some of the gas safety systems required for a gaseous fuel other than petroleum. It should be pointed out that currently these systems and others are included in the IGF, but it does not currently cover hydrogen as a fuel.

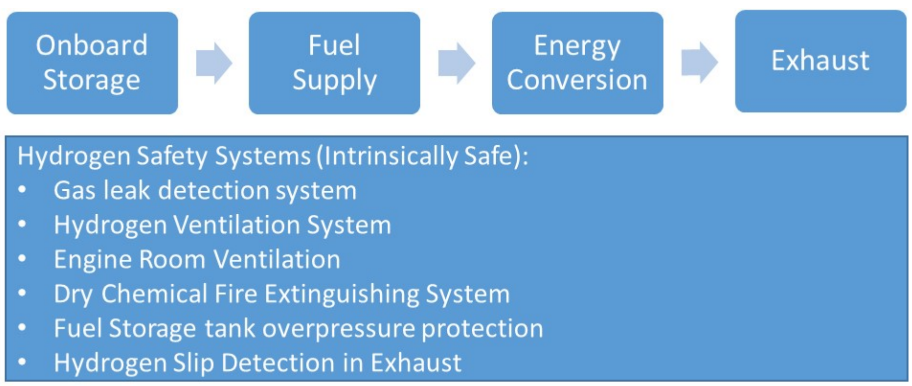

Figure 3. Shipboard Infrastructure Requirements

The final two blocks in Figure 2 detail the machinery required for conversion of the fuel into propulsive and hotel electrical load power. Current modern maritime vessel energy conversion systems are predominantly efficient diesel engines although some boiler-steam turbine and gas turbine systems are in operation. These systems receive the fuel and combust it to convert the energy into either propulsive

[17] International Maritime Organization. (2020b). *International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code)*. https://www.imo.org/en/OurWork/Safety/Pages/IGF-Code.aspx#:~:text=International%20Code%20of%20Safety%20for%20Ship%20Using%20Gases,operating%20with%20gas%20or%20low-flashpoint%20liquids%20as%20fuel.

power or electricity. After completing combustion, the exhaust gases created are ducted out of the engine, into an exhaust system that is then piped so the gases exit the ship.

Modern diesel engines are regulated through design requirements to meet more rigorous NOx and particulate emission requirements with new construction requiring Tier 3 IMO and Tier 4 EPA. Many engine manufacturers include after-exhaust devices, such as particulate traps and selective catalytic reduction devices, to meet emission criteria. Additionally, operators who use heavier intermediate fuels while operating in environmentally sensitive areas (ECAs) near shore have had to either equip their vessels to switch to a fuel containing less than 0.5% sulfur or install sulfur scrubbers into the exhaust gas stream.

All of these systems shown in Figure 2 - from the bunkering station to the exhaust gas stack outlet - will require some re-engineering, re-thinking, and in some cases will need to be re-imagined. Even methanol as a fuel will require different tank coatings and potentially fuel system component re-design. Many ships and vessels, whether operated inland, coastal, or deep sea, will need to be replaced, retired, or retrofitted to achieve the goals of IMO and the U.S. Administration. This is a daunting task, made more challenging by the fact that the vessels being designed and constructed in the coming years will be operational in 2050. The good news is that the IMO, member nations, and maritime industry have begun to focus on these targets with research and development, road mapping, and pilot projects to reduce GHG emissions.

The remainder of this report examines the GHG reduction from a slightly different angle. What if, instead of modifying all of the systems shown in Figure 3, and relying on the shoreside infrastructure systems to come on-line as shown in Figure 2, the problem is worked from the exhaust gas end of the system? What if Carbon Capture and Carbon Storage could be a quicker solution for the short-term and even part of the long-term solution for those vessels that may not be able to convert? This alternative solution could provide a means for older ships to meet a goal of net zero emissions even if they cannot be fully retrofitted to convert to a non-hydrocarbon fuel. Figure 4 shows the approach that will be examined in this proposed project.

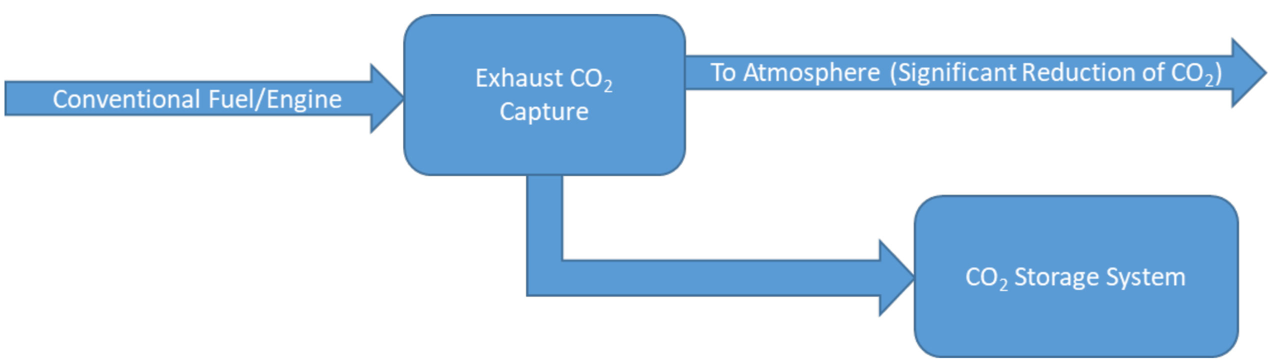

Figure 4. Exhaust Gas System Carbon Sequestration.

As described in the background, U.S. DOE and others worldwide have been working on carbon capture, carbon storage and transport, and carbon sequestration since the 1990s as a solution to reducing or eliminating greenhouse gas emissions. Mitsubishi will be inserting the technology on a ship in the next few years. Many studies and some shipboard demonstrations have already commenced or will be started soon. Section 3 will describe in detail the carbon capture and storage technologies as well as ongoing studies and projects.

What does carbon capture and storage look like for marine vessels? Although there are actually two discreet parts to the carbon capture and storage system as shown in Figure 5, only the shipboard portion will be discussed in detail. It is very important to understand that for marine carbon capture and storage to work as a GHG emission reduction methodology, it must be coupled with shoreside infrastructure to offload the CO_2 that is captured, transport it, and dispose of it either by re-purposing or sequestering it for long-term storage.

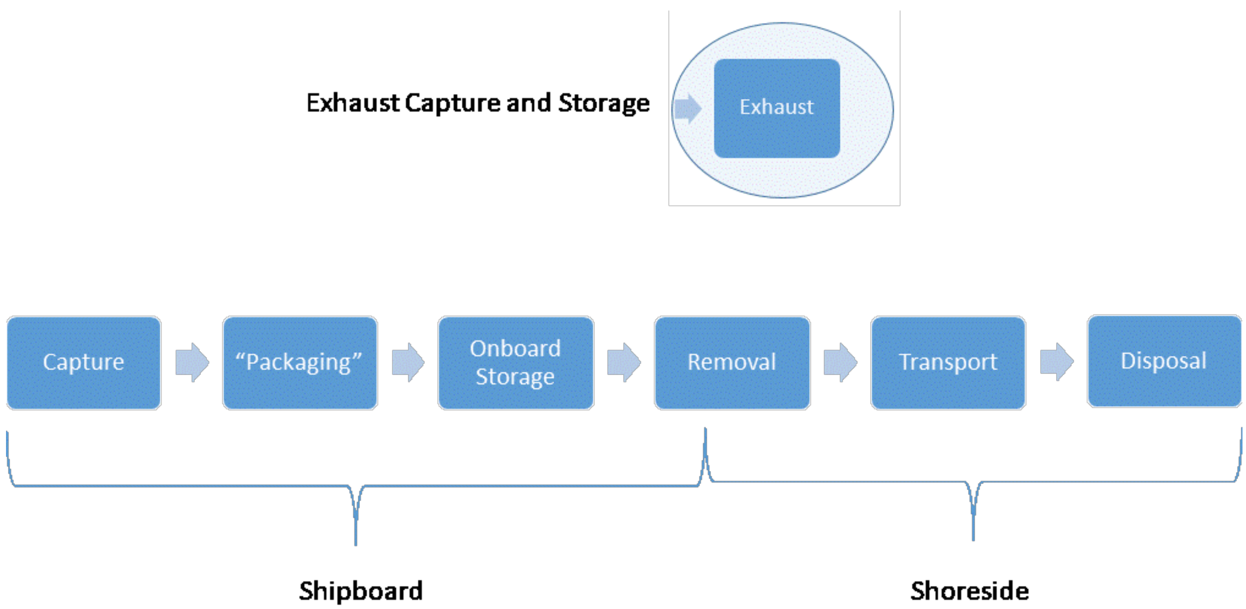

Figure 5. Complete Carbon Capture and Storage Technology

1.3.2 Challenges of Carbon Capture and Storage

There are several challenges with shipboard Carbon Capture and Storage application development. The U.S. DOE has been working on technologies for carbon capture for over 25 years, primarily for shoreside power generation plants. For the marine industry to take advantage of CCS, the challenges described in Table 1 must be overcome.

Table 1. Summary of Shipboard Carbon Capture and Storage Challenges

Challenge	Requirements to Overcome
Marinization	Equipment will require redesign and adherence to marine classification rules and regulatory requirements.
Naval Architecture	Equipment will need to be installed onboard a vessel without dramatically altering its seafaring characteristics and revenue-generating capacity.
Storage Considerations	After CO_2 is captured, it must be stored until offloaded. For every pound of fuel burned, three pounds of CO_2 is generated. CO_2 storage will need to be incorporated into a vessel's ballast planning since it adds two more pounds of weight for each pound of fuel burned.
Energy / Power Requirements	Capturing and storing CO_2 requires more energy in the form of heat and/or electrical power which has a double whammy effect – the ship may need to burn more fuel to generate the energy required, which equates to higher fuel costs and the need to pull out and store even more CO_2.
CO_2 Removal	Shoreside CO_2 transport, use, and sequestration are all under development. Currently, this does not exist at any port worldwide in large capacity.

Finally, an analysis of trade-offs will be required to define optimal CO_2 capture rates, storage capacity, and capital expenditure (CAPEX). Studies have already been done, and more are underway, to show that while complex, shipboard CCS is certainly possible. A recent study conducted by OCCI – Stena, which modeled what they considered the worst-case scenario ship, a Suezmax Crude Oil Tanker, concluded that while the estimated costs were higher than expected, the results encouraged them to pursue a demonstration and that marine carbon capture can play a role in meeting the IMO 2050 GHG reduction goals. [18]

[18] Stena Bulk. (2021). *Is Carbon Capture on Ships Feasible?* Safety 4 Sea. https://safety4sea.com/wp-content/uploads/2021/11/OGCI-STENA-Is-carbon-storage-technically-feasible-2021_11.pdf.

2 Marine Carbon Capture and Storage (CCS) Technology

As discussed in Section 1.3.1, a complete marine carbon capture system will need to include carbon capture equipment, packaging (CO_2 processing equipment) for storage, and storage tanks for onboard storage until reaching shore to offload. Each part of the capture system is essential for shipboard CO_2 management and is designed to work together. Section 2.1 discusses the Carbon Capture technologies that are under development as well as their status and applicability to vessels. Section 2.2 discusses the different options for carbon storage on board vessels. Finally, Section 2.3 details the carbon packaging requirements to process the CO_2 into a storable state. These sections are provided in this order because while packaging happens prior to storage, the methods and requirements are dictated by the capture method and the storage method.

2.1 Carbon Capture

Carbon capture of combustion gases first occurred in a chemical plant in California in 1978.[19] The first use was not due to climate or GHG concerns, but rather the need for cheap CO_2 for the processes in the chemical plant. Using an amine process patented in the 1930s, the plant successfully demonstrated capturing CO_2 from boiler flue gas.

Two pathways are currently being developed for capturing CO_2 from boilers, industrial processes and internal combustion engines – pre-combustion and post combustion. In 2013, the U.S. DOE developed goals for carbon capture systems. The first goal is to develop second-generation technologies at a cost of less than $40 per tonne of CO_2 captured by 2025. By 2035, the objective is to develop carbon capture technologies that cost less than $10 per tonne of CO_2 captured. One of the drivers for cost is the concentration of CO_2 emissions resulting from the processing. For highly concentrated process streams like ethanol production, the cost is currently between $15-25 per tonne of CO_2. However, it can range $40-120 per tonne of CO_2 for dilute process streams like power generation.[20] In considering carbon capture onboard vessels, what typically adds to the price per tonne is the gas processing and storage for the duration of the voyage. Therefore, the storage tank cost is significant and is discussed in more detail in the next section.

The following sections discuss the CO_2 capture technologies under investigation and development. Some methods are more mature than others and each tends to work better for certain applications and CO_2 concentrations and have different efficiency and power requirements. Section 2.1.1 briefly discusses pre-combustion carbon capture; however, it is not anticipated that this technology will be used shipboard. Section 2.1.2 discusses post-combustion systems. These technologies remove the CO_2 in the exhaust gas stream after combustion has occurred. Five categories of technology, all post-combustion capture, will be discussed:

[19] Herzog, H. J. (2018). *Carbon Capture*. The MIT Press. https://doi.org/10.7551/mitpress/11423.001.0001.
[20] Baylin-Stern, A., & Berghout, N. (2021). *Is carbon capture too expensive?* International Energy Agency. https://www.iea.org/commentaries/is-carbon-capture-too-expensive.

- Chemical Absorption
- Membrane Separation
- Physical Separation (adsorption)
- Cryogenic Separation
- Oxy-Fuel Separation (oxy- combustion)

For each of the sections, a brief description of the technology is provided.

2.1.1 Pre- Combustion Carbon Capture

Pre-combustion capture separates the CO_2 from the fuel prior to combustion, leaving mainly hydrogen for use. Typically, this process is done onshore. There is, however, one onboard marine concept design developed to take advantage of pre-combustion separation to produce hydrogen from methanol fuel while capturing CO_2 for storage and reuse. This proposed marine system is called the 'HyMethShip' concept, which uses an onboard pre-combustion CO_2 capture system as part of the process.[21] By sending the CO_2 to a methanol production facility powered by renewable power, the CO_2 can be reused again for shipboard fuel. This process is often referred to as carbon circulation since much of the CO_2 from the methanol is recycled into new fuel.

More classical techniques for producing carbon-free fuel start with a hydrogen containing feedstock. If for example, a hydrocarbon feed is used to produce hydrogen, CO_2 is generated. The CO_2 is captured and sequestered as part of the fuel production processing. If however, water is used as the feedstock and is separated using electrolysis powered by wind or solar power, CO_2 capture and sequestration is not required. Pre-combustion Capture is not included in this study.

2.1.2 Post Combustion Carbon Capture

2.1.2.1 Chemical Absorption

Chemical absorption capture systems are the most studied and mature of the carbon capture technologies. A typical chemical absorption capture flow sheet is shown in Figure 6 for a coal-fired power plant.[22] Flue gas pressure must be boosted slightly to push the flue gas through the absorber and other downstream equipment. The flue gas typically must be pre-treated and cooled in a pre-scrubber to reduce SOx and/or NOx to low levels to minimize contamination of the solvent. Flue gas exiting a pre-scrubber is contacted by lean (low CO_2 content) solvent in the absorber in a counterflow direction where the CO_2 is absorbed. Cleaned flue gas flows out the top of the absorber and rich (high CO_2 content) solvent flows out the bottom of the absorber to the lean/rich heat exchanger. The top stage in the absorber uses a wash to minimize the discharge of solvent from the absorber. The rich solvent is pre-heated before flowing to the stripper. The solvent is thermally regenerated in the stripper using steam

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[21] Malgren, Elin, Brynolf, Selma, Fridel, Eric, et al, *The Environmental Performance of a Fossil-Free Ship Propulsion System with Onboard Carbon Capture – A Life Cycle Assessment of the HyMethShip Concept*, Sustainable Energy & Fuels, Royal Society of Chemistry, 2021, 5, 2753.

[22] James R, Keairns D, et al. *Cost and Performance Baseline for Fossil Energy Plants Volume 1 : Bituminous Coal and Natural Gas to Electricity. NETL Rep Pub-22638*. 2019;1:598.

heat. The hot CO_2 flows out of the top of the stripper to a condenser where solvent exiting the stripper is condensed so it can flow back to the stripper. The lean solvent is then cooled in the lean/rich heat exchanger before being injected into the top of the absorber, completing the cycle for the solvent. Pumps to circulate the solvent between the absorber, stripper, and lean/rich heat exchanger are not shown.

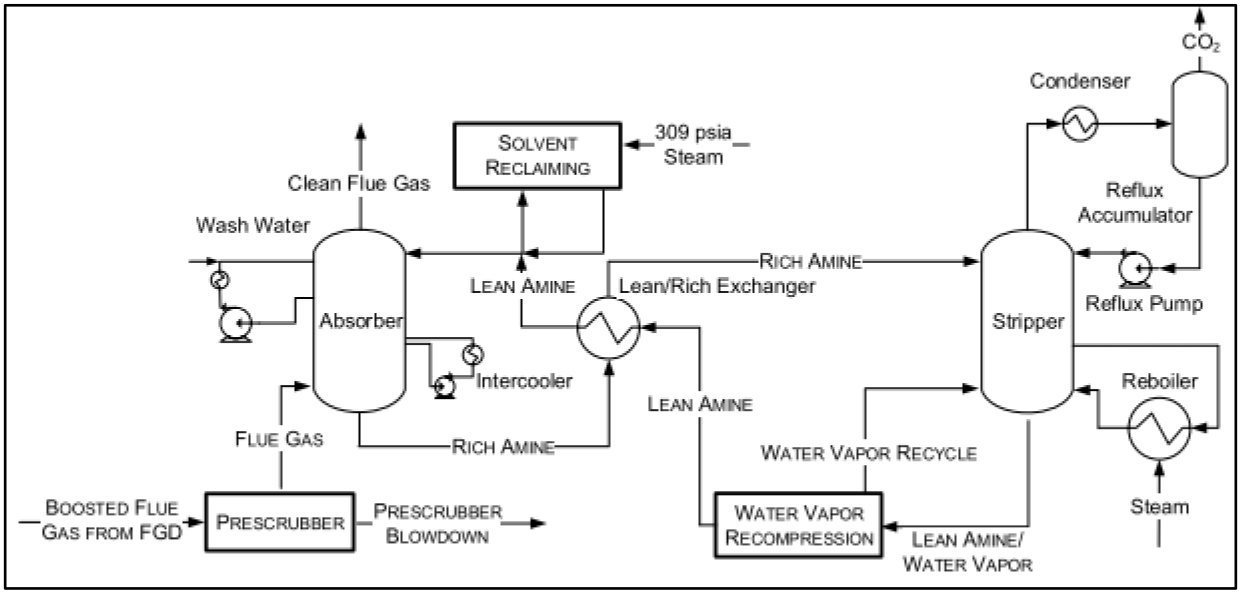

Figure 6. Typical Chemical Absorption System for Flue Gas Carbon Capture

All proposed chemical absorption systems have the same fundamental process flow diagram with the differences being the solvent characteristics and some minor process configuration modifications. The objectives of modifying the solvent and flowsheet include:

- maximize absorption capacity,
- reduce reboiler heat duty and required stripping temperature,
- stability in presence of oxygen and high temperature,
- reduce viscosity to subsequently reduce pumping power, improve heat transfer efficiency, and increase mass transfer rates,
- reduce corrosivity,
- reduce volatility to minimize carryover in the treated flue gas,
- reduced toxicity,
- reduced cost.

The most common solvent used for this process is known as monoethanolamine, or abbreviated as MEA, and is typically in an aqueous solution of up to 30% by weight. The process is a closed-loop system and requires energy for re-heating the rich amine to strip out the CO_2 from the capture process. For shipboard use, this system requires either use of high temperature exhaust gas or an auxiliary boiler to add heat to the amine for removal of CO_2.

Improvements can be made to the energy requirements through substitution of solvent types. A review of general solvent types (primary amines, secondary amines, tertiary amines, piperazine, amine blends, ionic liquids, and non-aqueous organic amine blends) was assembled by an international group of capture and storage experts.[23] Several companies have developed solvents that are commercial or near commercial including Shell (CanSolv process), Fluor (Econamine)[24], Mitsubishi (KM CDR Process – KS-1 solvent)[25], and Linde-BASF (OASE blue solvent).[26] Research work continues on increasing solvent life, improving process efficiency, and reducing the energy requirements of this process.

There are several ongoing shipboard tests and research projects using this absorption technology. Section 1 describes some of these projects including the CC-Ocean Project that demonstrated shore-side Mitsubishi absorption technology on a K Line ship. Section 2 also describes some of the technical studies about applying absorption technology to shipboard carbon capture use.

It is also noteworthy to mention the testing and research that has begun to determine whether existing marine SOx scrubbing units can be modified to capture CO_2 along with SOx. Sections 3.1.3 and 3.1.9 discuss testing done by Alfa Laval and Langh Tech to successfully demonstrate lower rates of carbon capture of around 8 – 10 percent using this technology. Many details still need to be worked out for onboard storage and CO_2 separation from process fluids, but it may provide a short-term carbon capture benefit.

2.1.2.2 Membrane Separation

Membrane separation technology is another method under development for carbon capture. Membranes are thin layers of materials permeable to CO_2 acting in similar fashion to other marine applications like filter systems. Research into membrane design continues because of their lower capture rates than chemical absorption technology as the membranes are designed with both permeability (faster porosity) and selectivity (CO_2 gas only) in mind. Unlike chemical absorption systems, membrane capture systems are more compact, much more scalable, and do not have toxic and/or corrosive liquids flowing through the plant.

A flow diagram for a single-stage membrane system is shown in Figure 7.[27] Cooled flue gas flows through a booster fan and then through the primary CO_2 membrane where some of the CO_2 permeates the membrane before the CO_2-depleted flue gas is directed to the stack. The driving force for

[23] Bui M, Adjiman CS, Bardow A, et al. *Carbon capture and storage (CCS): The way forward*. Energy Environ Sci. 2018;11(5):1062-1176. doi:10.1039/c7ee02342a.

[24] Reddy S, Yonkoski J, Rode H, Irons R, Albrecht W. (2016) *Fluor's Econamine FG PlusSM Completes Test Program at Uniper's Wilhelmshaven Coal Power Plant*. *Energy Procedia*. 2017;114: pages 5816-5825. doi:10.1016/j.egypro.2017.03.1719.

[25] 'Mitsubishi Heavy Industries. (2017) *MHI' s Carbon Capture Technology*. 2017 CO_2 ROZ Conf carbon Manag Work. https://www.co2conference.net/wp-content/uploads/2017/12/4-MHI-Slides-on-the-PetroNova-Project.pdf.

[26] Lunsford L. *Front End Engineering Design of Linde-BASF Advanced Post-Combustion CO_2 Capture Technology at a Southern Company Natural Gas-Fired Power Plant*, DE-FE0031847. 2021.

[27] Baker RW, Freeman BC, Kniep J, Merkel T. *Large Pilot Testing of the MTR Membrane Post-Combustion CO_2 Capture Process*. Retrieved from: https://edx.netl.doe.gov/dataset/large-pilot-testing-of-the-mtr-membrane-post-combustion-co2-capture-process.

membrane operation is provided by a vacuum pump. The combined permeate/inert stream from the CO_2 purifier passes through a second membrane. The retentate from the second membrane is mixed with the untreated flue gas. The permeate from the second membrane is directed to a purification system to remove nitrogen and other gases that pass through the membrane to provide a purified CO_2 stream for storage and sequestration.

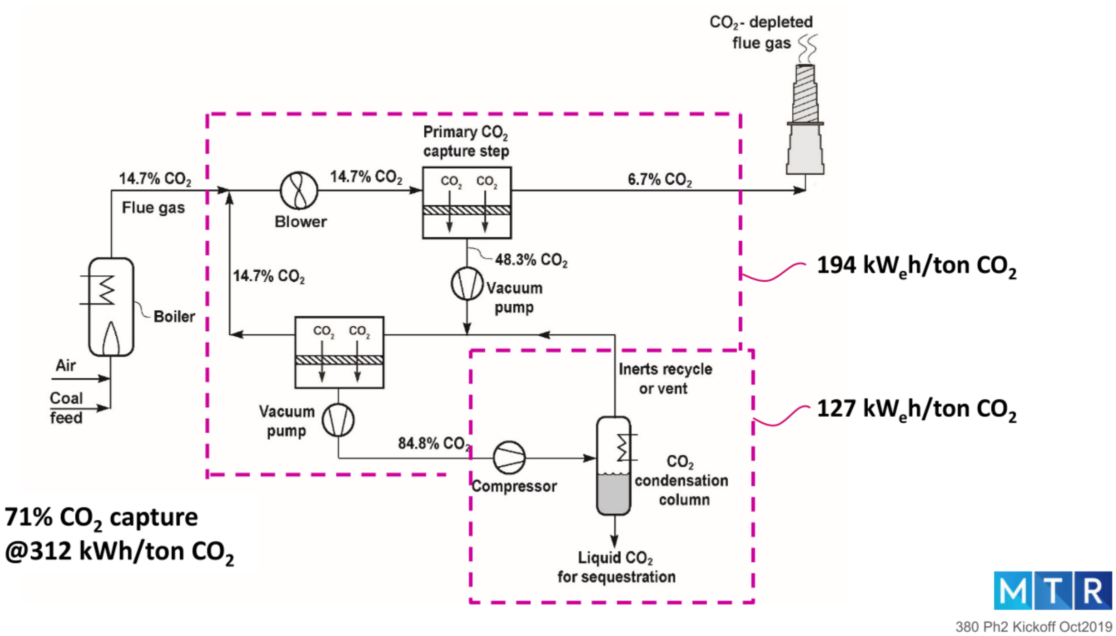

Figure 7. Single Stage Carbon Capture with Membrane Separation

It is possible to increase the capture efficiency by going to a two-stage system as shown in Figure 8.[27] A second membrane is added to the system using the combustion air as a sweep gas. Permeated CO_2 mixes with the combustion air reducing the concentration of CO_2 in the CO_2-depleted flue gas and increasing the concentration of CO_2 in the untreated flue gas. The purification system is still required to provide a pure stream of CO_2 for storage and/or sequestration.

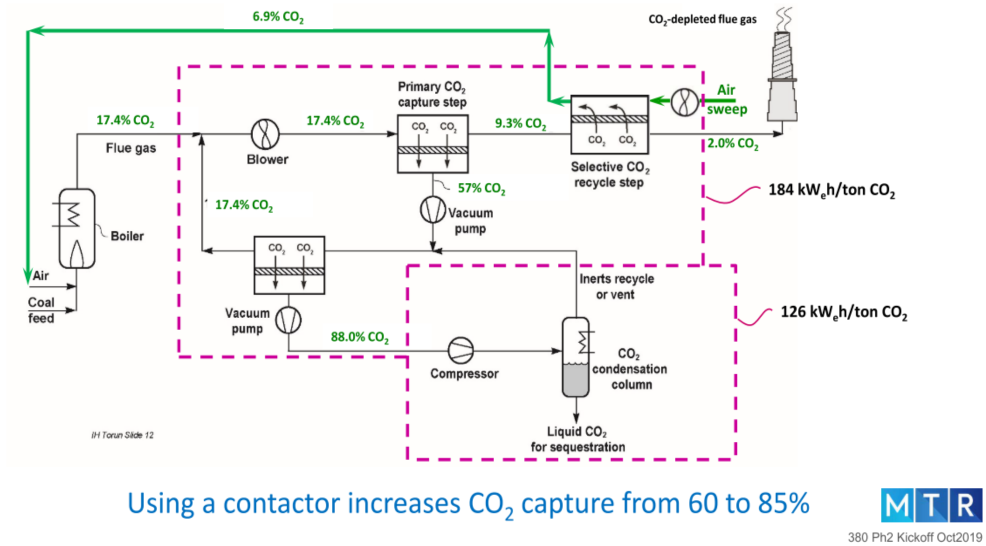

Figure 8. Carbon Capture with Contactor

Current research focuses on membranes with higher selectivity (increases concentration of permeate), higher permeance (reduces required membrane area), and more contaminant tolerance. There are numerous developers of membrane material, but Membrane Technology and Research (MTR) is one of the leaders in this technology in the US. MTR is a supplier of commercial membranes for other applications. MTR has completed a 1 MW pilot test and is currently performing a front-end engineering and design (FEED) study for a 420 MW plant and has an ongoing project to build, operate, and demonstrate a 10 MW pilot test. There were no active marine projects found during the literature search that were either evaluating or researching this technology.

2.1.2.3 Physical Separation (Adsorption)

Section 2.1.2.1 discussed absorption systems for CO_2 Capture. This section discusses adsorption systems. The fundamental difference is that with chemical absorption systems, CO_2 is absorbed into the amine or solvent solution and through the addition of heat releases the CO_2 while the sorbents in adsorption systems are designed to cause CO_2 to adhere to the surface of the materials. The issue with sorbents is that they often allow other gases like water vapor to adhere to them and compete with CO_2 harvesting. Selection of the right sorbent material permits large amounts of CO_2 to be captured and then released with much lower energy requirements for the release of CO_2.

One configuration for a physical separation (adsorption) capture system being developed by InnoSepra[28] is shown in Figure 9 for a coal-fired power plant.[29] Flue gas pressure is first boosted, then cooled. Moisture is removed from the flue gas in a moisture adsorber. Moisture must be removed from the flue gas before passing to the CO_2 adsorption bed since the moisture will compete with the CO_2 for adsorption sites/capacity. In a unique process, the dehydration sorbent is regenerated with the cleaned flue gas.

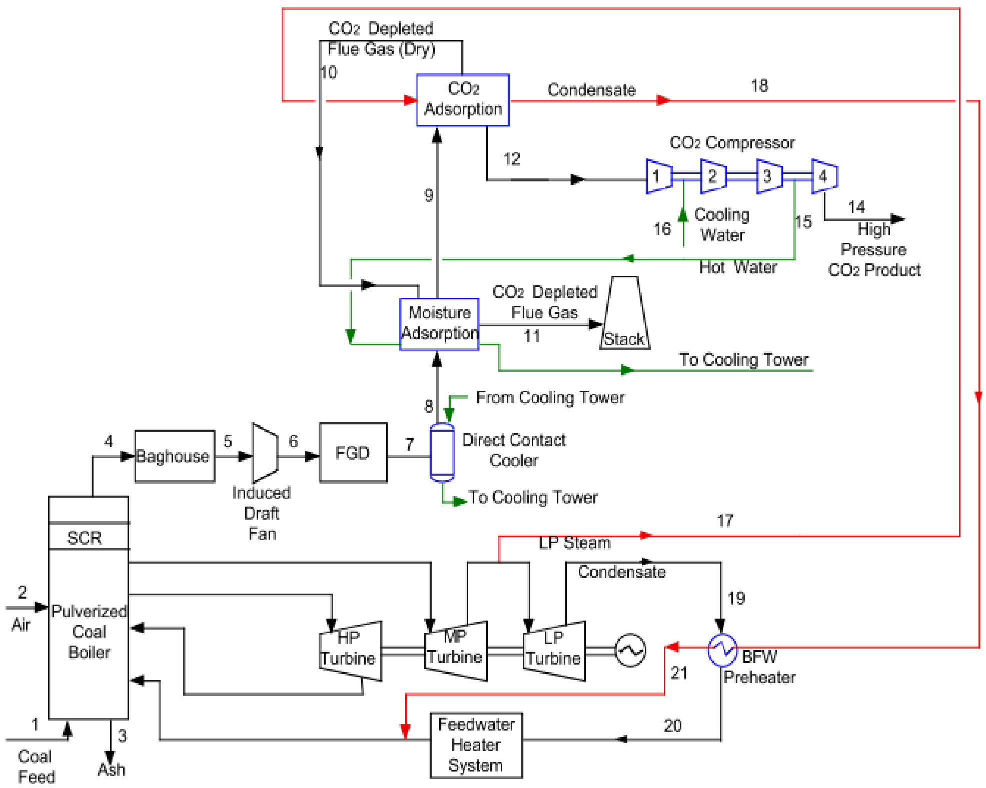

Figure 9. Flows for a Physical Separation (adsorption) System Designed for a Coal Plant

A process flow diagram of InnoSepra's capture system is shown in Figure 10.[30] As typically done with adsorption systems, one bed is adsorbing the contaminant while the other bed(s) is being regenerated. Thermal regeneration of the carbon capture sorbent is accomplished with 1.6 GJ/tonne CO_2 steam at 110°C.

[28] Jain, R., & Lemcoff, N. (2021). *Transformational Sorbent-Based Process for a Substantial Reduction in the Cost of CO_2 Capture* [Slides]. National Energy Technology Laboratory. https://netl.doe.gov/sites/default/files/netl-file/21CMOG_PSC_Jain.pdf.

[29] Jain, R. (2014). *Bench-Scale Development & Testing of a Novel Adsorption Process for Post-Combustion CO_2 Capture* [Slides]. National Energy Technology Laboratory. https://www.netl.doe.gov/sites/default/files/event-proceedings/2014/2014%20NETL%20CO2%20Capture/R-Jain-InnoSepra-Bench-Scale-Development-And-Testing.pdf.

[30] Jain R. *Bench Scale Development of a Novel Adsorption Process for Post-Combustion CO_2 Capture*. Vol 5;18.; 2015. doi:10.36076/ppj/2015.

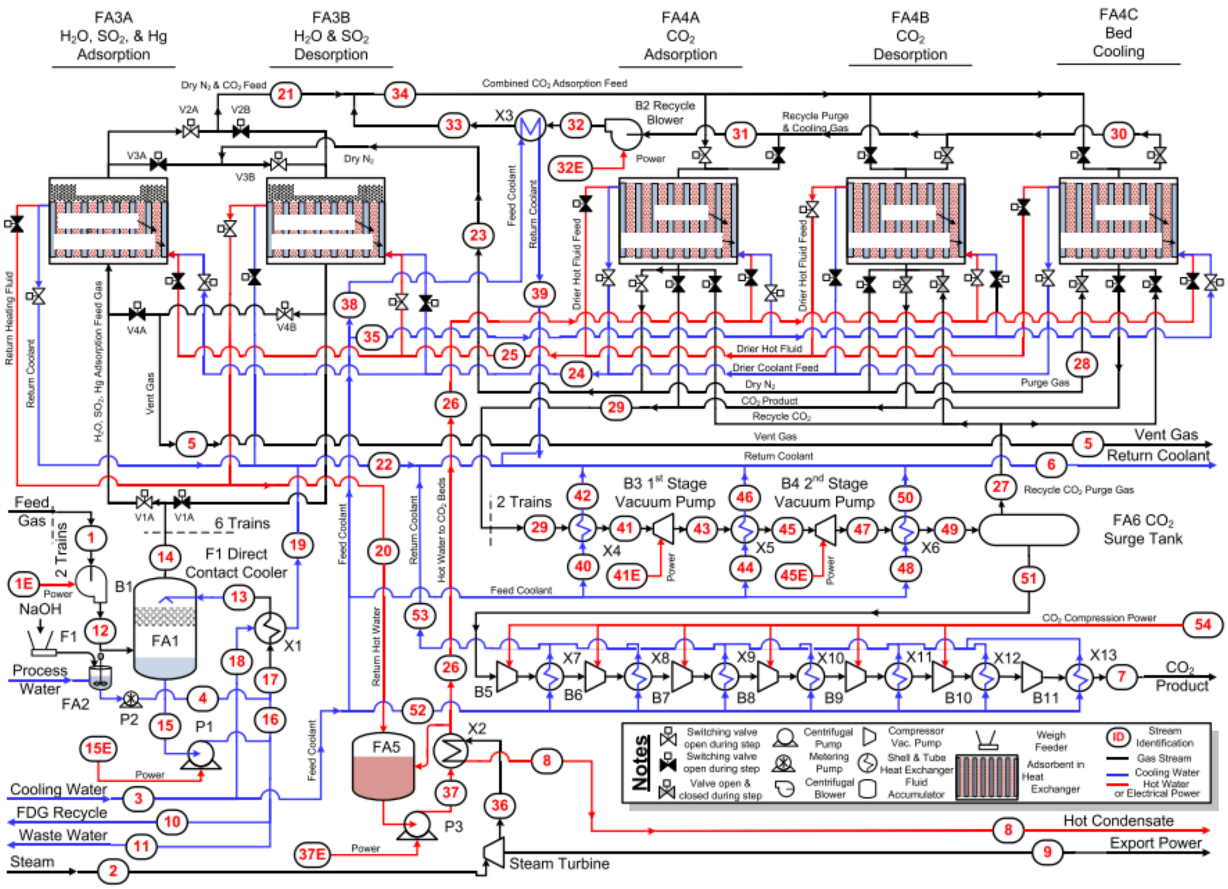

Figure 10. Detailed Flow Diagram for InnoSepra's Physical Separation (adsorption) Carbon Capture System

Other companies are developing physical separation adsorbents and adsorbent systems as well. Two of the more notable in the U.S. include TDA[31] and ADA.[32,33] The focus of these developers are sorbents with higher CO_2 adsorption capacity, higher CO_2 selectivity, and better contaminant tolerance.

InnoSepra has completed a 0.05 MW field test on flue gas from a coal-fired power plant. Demonstration of large adsorption systems for gas dehydration, hydrogen purification, nitrogen generation, oxygen generation, etc. is being leveraged to design physical separation (adsorption) systems for CO_2 capture.

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[31] Elliott, J., & Yi, F. (2019). *Update on Pilot Unit of Sorbent Based Post-Combustion CO_2 Capture* [Slides]. National Energy Technology Laboratory. https://netl.doe.gov/sites/default/files/netl-file/J-Elliott-TDA-Sorbent-CO2-Capture.pdf.

[32] Sojostrum, S. (2015). *Evaluation of Solid Sorbents as a Retrofit Technology for CO_2 Capture*. ADA-ES Inc. https://www.osti.gov/servlets/purl/1261627.

[33] Sjostrom S, Krutka H, Starns T, Campbell T. *Pilot test results of post-combustion CO_2 capture using solid sorbents.* Energy Procedia. 2011;4:1584-1592. doi:10.1016/j.egypro.2011.02.028.

In 2021, Caterpillar purchased CarbonPoint Solutions to add carbon capture to their growing integrated business portfolio. CarbonPoint has some patented technology for carbon capture for lean burn natural gas engines and gas turbines. Their technology includes adsorption technology, called a molecular sieve, which adsorbs CO_2 in small compact beds. Figure 11 shows their capture solution.[34] So far, no marine projects are scheduled, but Caterpillar is piloting a Solar T60 gas turbine capture plant and a G3606 natural gas engine in 2022.

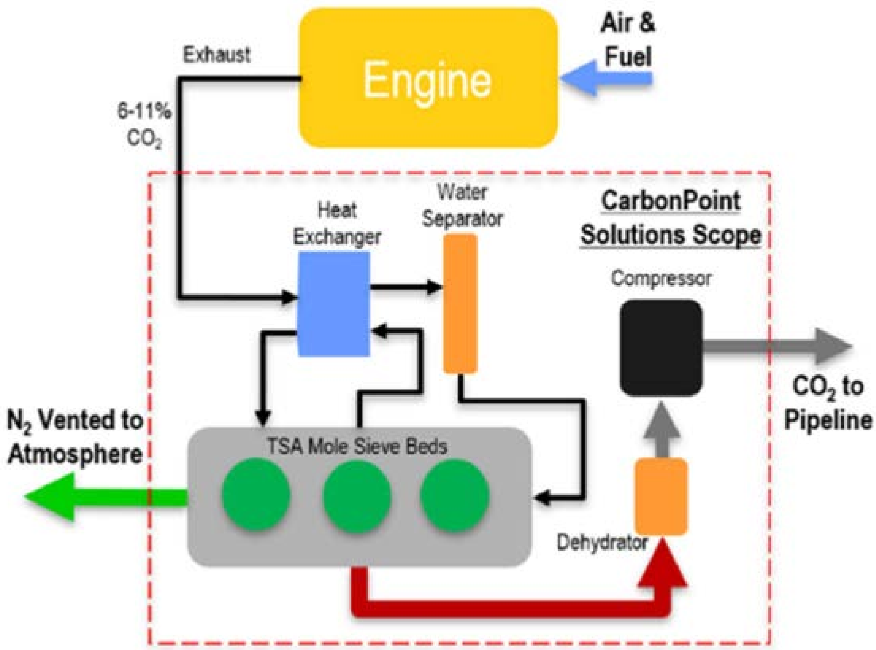

Figure 11. Caterpillar CarbonPoint Solutions Flow Diagram

2.1.2.4 Cryogenic Separation

Cryogenic separation processes for CO_2 removal function by cooling the exhaust gas stream to temperatures of minus 120 to minus 135°C, freezing the CO_2, and separating the solid CO_2 from the gas stream. [35] Significant electrical power is required to provide the refrigeration to cool the combustion gases causing the CO_2 to separate from the gas stream without any chemicals or sorbents. Efficient design of heat exchangers and refrigeration plant is essential to reduce the power required to operate the process. Flow diagrams of two different concepts are shown in Figure 12 and Figure 13.

Figure 12 shows a process being developed by Sustainable Energy Solutions (SES).[36] In this process, a refrigeration loop is used to transfer heat from the incoming flue gas stream to the outgoing flue gas

[34] Caterpillar Capture Presentation (2022) *Whatever the Challenge, There's Caterpillar.*
[35] Baxter L, Hoeger C, Stitt K, Burt S, Baxter A. *Cryogenic Carbon Capture^{TM} (CCC) Status Report*. SSRN Electron J. 2021;(March):1-11. doi:10.2139/ssrn.3819906.
[36] Baxter, L., & Stitt, K. (2017). *Cryogenic Carbon Capture Development* [Slides]. National Energy Technology Laboratory. https://www.netl.doe.gov/sites/default/files/2017-12/L-Baxter-SES-Cryogenic-Carbon-Capture.pdf.

stream. The solid CO_2 is compressed in a novel solid compressor before being liquefied in the heat recovery system and then sent on to either be sequestered or stored.

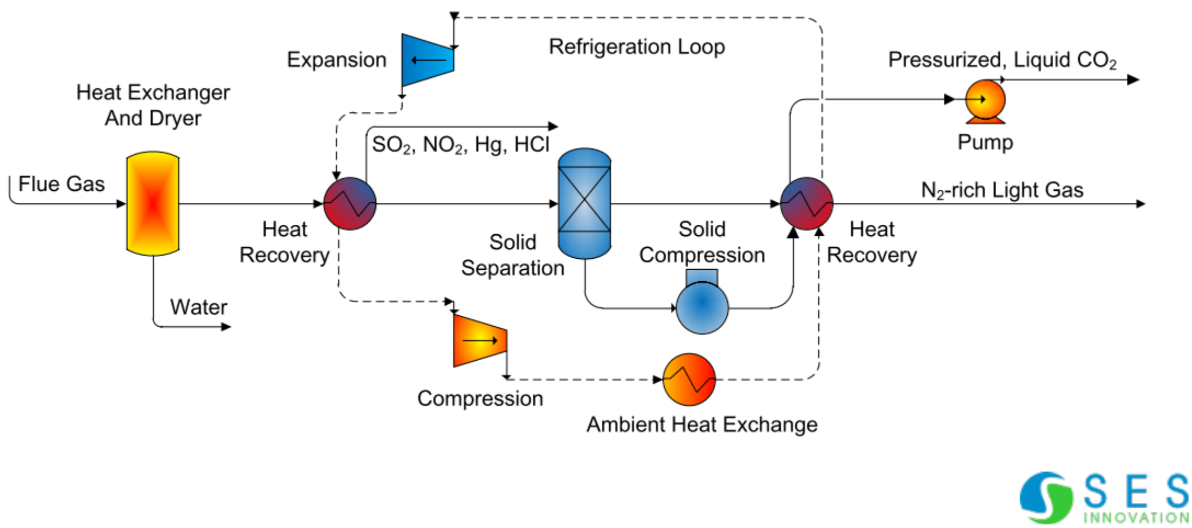

Figure 12. Flow Diagram of Cryogenic Separation Carbon Capture System Producing Solid CO_2

Figure 13 shows a concept being developed by PMW Technology.[37] The flue gas is precooled in the cooler-dryer to approximately minus 100°C. Further cooling to deposit CO_2 as frost is accomplished using a moving bed of cold metallic beads in the separator. Cooling and heating in the separator is accomplished using an integrated refrigeration circuit.

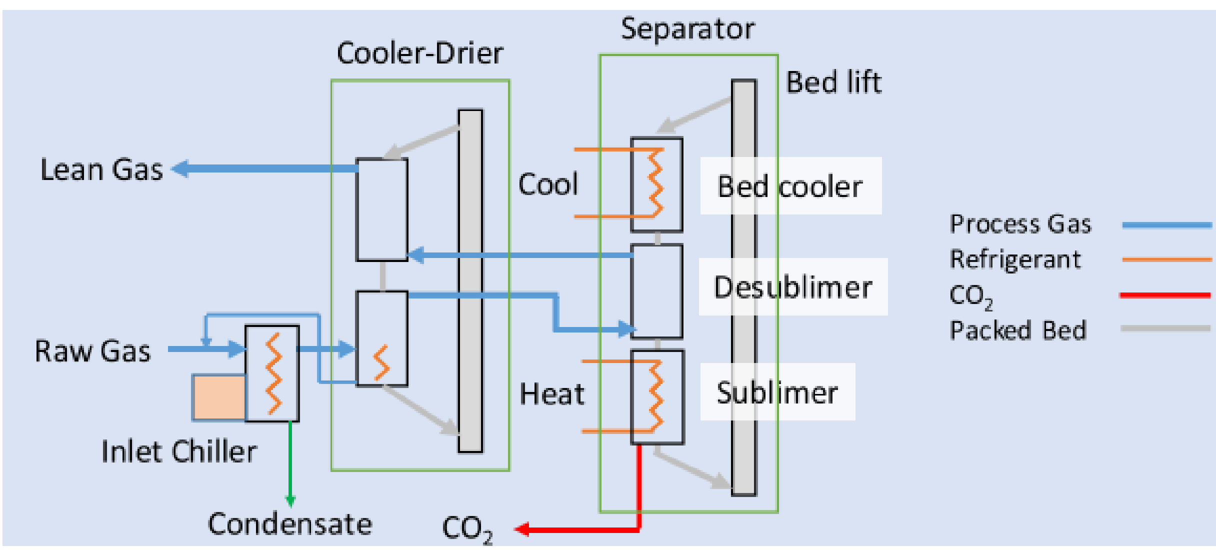

Figure 13. Flow Diagram of Cryogenic Separation Capture System Producing Gaseous CO_2

[37] Willson P, Lychnos G, Font-palma C. (2020) *Advances in Moving Bed Cryogenic Carbon Capture*. PMW Technology, University of Chester.

The status of development includes demonstration at 0.05 MW (1 tonne CO_2/day) by SES. While no literature was found regarding a demonstration of the PWM concept was found, the U.K Transport-Technology issued a 2019 marine carbon capture project study that include PMW technology. Section 3.2.5 provides a discussion of the report.

Chart Industries Sustainable Energy Solutions (SES) is developing their Cryogenic Carbon Capture (CCC) technology. Their process includes using a direct contact cooling material to freeze the CO_2 out of the exhaust gas. According to Chart, their technology is about half the cost of current CCS alternatives, produces a high purity CO_2 at a high capture rate, and is easily retrofitted. What makes their system appealing is that since the output is a liquid CO_2, it is ready for shipboard storage without any further processing requirement. Currently, SES is doing small pilot-scale system testing and is building their first commercial-scale demonstration. They are evaluating maritime applications at present.

2.1.2.5 Oxy-Fuel Separation (Oxy-Combustion)

The final carbon capture technology included in this report relates to separating the traditional elements of combustion so that the oxidant is a relatively pure stream of oxygen. The oxy-fuel separation process, shown in Figure 14, is a process where the oxidant for the combustion is a mixture of oxygen and re-circulated CO_2.[38] Typically ½ to ¾ of the exhaust gas, predominantly CO_2, is re-circulated and mixed with the oxygen to temper the combustion temperature. In an oxy-fuel separation process, the flue gas is predominantly CO_2 with a few percent H_2O. The bulk of the H_2O can be removed by cooling and condensing the water. Contaminants from the highly concentrated stream of CO_2 are removed in a distillation column purification unit. The purified CO_2 can then be compressed for transport and storage.

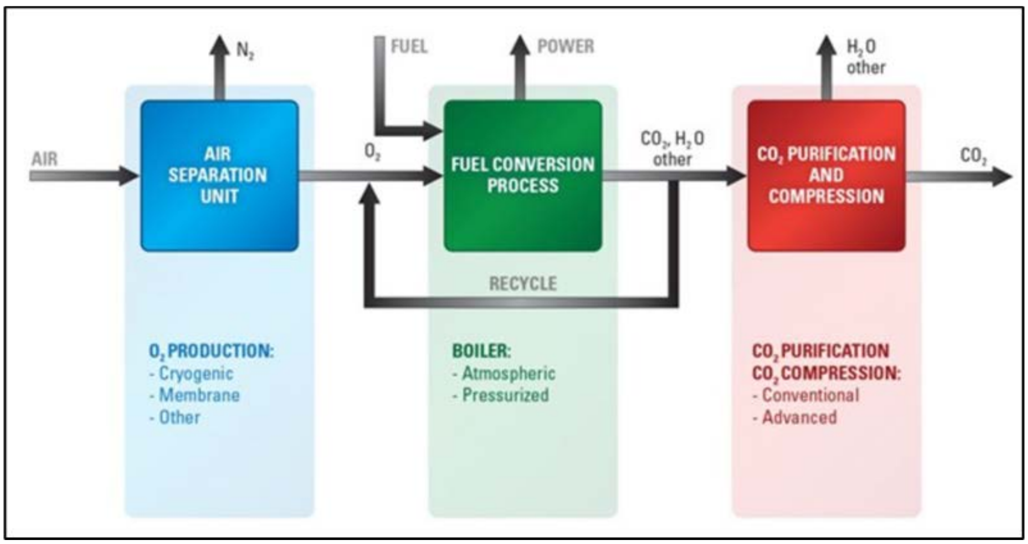

Figure 14. Oxy-Fuel Separation Block Flow Diagram

[38] *Oxy-Combustion*. (n.d.). National Energy Technology Laboratory. https://netl.doe.gov/node/7477#:~:text=Technology%20Laboratory’s%20(NETL)%20Transformative%20Power,instead%20of%20air%20for%20combustion.

While oxy-fuel separation has been significantly researched for boilers for stationary power plants, it is little more than a concept for internal combustion engines at this time. Much of the developmental research has been on oxygen separation. While cryogenic air separation has been commercial for decades, the capital and operating costs are quite high. Significant research over the last decade has been on Ion Transport Membranes (ITM) but this technology is yet to be commercialized.

2.1.3 Marine Application of Carbon Capture Technology

The overwhelming majority of research on carbon capture technologies has focused on stationary power generation. Recently, U.S. DOE has been funding projects to develop carbon capture for other industrial processes that have a high carbon intensity like cement plants and ammonia production. This research and demonstration work is essential to deploying a carbon capture solution; however, once these technologies are successful onshore, they need to be developed further to meet marine requirements.

Shipboard carbon capture has some considerations that differ from stationary plant carbon capture installations. As discussed in Section 1.3.2, space and weight are more of a premium on shipboard installation than at a stationary power plant because the equipment size and weight can reduce cargo-carrying capability, which relates to revenue as well as impact ship stability and performance. Also, any storage requirements for consumables such as solvents or sorbents can impact both safety and ship design.

For stationary power capture systems, capture efficiency and auxiliary power requirements are reasonably well documented. However, footprint and weight are only available for cases where a front-end engineering and design (FEED) study has been conducted. This is very important to the application for marine vessels with size restrictions and footprint availability are often a premium. Additionally, the CO_2 that is generated is typically then sent through pipelines or tank trucks to either be used or sequestered. For marine vessels, once the carbon is captured it needs to be processed and stored onboard until it can be offloaded at a port facility and appropriately re-used or sequestered.

What is likely the biggest challenge with carbon capture in the marine industry may also be the biggest advantage. Shoreside industrial and power facilities come in different sizes, outputs, and operations, but nearly all with the same goal – high efficiency production and output. On the other hand, marine vessels come in many shapes, sizes, purposes, and operations. Vessels use hydrocarbon fuels for two purposes, propulsion and electrical power generation, for various operational purposes. Therefore, adapting shoreside capture across the maritime industry fleets is rather unlikely. However, it is extremely likely for certain vessel designs, trades or operations the technology will have a place since there is such a variety of applications.

For more details about evaluating shoreside capture technology for marine application refer to Section 3.1 (Demonstration Projects) and Section 3.2 (Technical Studies). Many of these projects include carbon capture and storage (CCS).

2.1.4 Summary and Comparison of CO_2 Capture Technologies

A detailed comparison of carbon capture technologies for shipboard applications would require a techno-economic analysis for each technology on a specific type of ship. This would require an effort beyond the scope of this study. As an alternative, a rough comparison of the technologies is provided with the aid of information provided in Table 2.

Table 2. Comparison of Capture Technologies

	Chemical Absorption	Membrane Separation	Physical Separation (Adsorption)	Cryogenic Separation	Oxy-Fuel Separation (oxy-combustion)
SO_2 and NOx Removal?	Yes	No	SO_2 removal integral to process	Yes	In CO_2 purification process
Pre-Drying Required?	As part of pre-cooling	No	Water removal integral to process	Yes	Yes
Capture Efficiency, %	90+	60-85	90+	90+	90+
CO_2 Drying Required?	Yes	As part of purification	No	No	Yes
CO_2 Purification Required?	No	Yes	No	No	Yes
Thermal Energy (Heat) Required?	High	None	Medium	None	None
Electric Power Required?	Low	Medium	Low	High	High
Maturity	High	Medium	Medium	Low	Low
Major Advantages	- High purity CO_2 - Commercial readiness	- Simplicity - No moving parts	- Minimal electrical power and moderate thermal energy required	- No chemicals, sorbents, or membranes that can be contaminated	- Significantly eliminates NOx emissions
Major Disadvantages	- Amines are toxic and corrosive - Requires significant amount of thermal energy	- Requires purification unit to achieve acceptable CO_2 quality	- More complicated valving and piping required, as compared to other solutions	- Significant electrical power required - Handling/transport of low temperature solid CO_2 is problematic - Heat integration is complicated	- Significant generation and handling of pure oxygen is required

Chemical absorption capture systems have the highest level of maturity and are the technology most studied for shipboard carbon capture largely because of its level of commercialization. Most solvents require removal of SO_2 and NOx to single digit ppm levels to avoid significant contamination of the solvent. As with all of the technologies, for chemical absorption systems it is necessary to reduce the temperature and reduce the water content of the flue gas. Capture efficiencies of 90 plus percent are easily achieved. For many years, the target capture efficiency for stationary power was 90%. However, more recently the target has been increased to ~97%. Solvent systems require high amounts of thermal energy to regenerate the solvent and low to moderate amounts of electrical power to circulate the solvent and boost the flue gas pressure to account for the absorber pressure drop. Most solvents are also toxic and it is essential to take precautions to minimize solvent emissions with the cleaned flue gas.

Membrane separation capture systems are simple and do not require moving parts. Membrane systems do not require thermal energy but they do require moderate amounts of electrical power. The biggest disadvantages of the membrane systems are lower capture efficiency (60-85%) and the purity of the captured CO_2 is not acceptable for storage without a relatively complicated purification system. It would not be practical to store the non-purified CO_2 onboard ship, for purification later on shore, because the volume of the captured non-purified CO_2 would be prohibitively larger than the purified CO_2. Weight, volume, and storage options of captured CO_2 are discussed in further detail in Section 2.2.

Physical separation (adsorption) capture systems have an integral dehydration step which results in a dry CO_2 product. Because of the high selectivity of sorbents, no purification of the CO_2 product is required and thus the CO_2 can be directly pressurized and liquefied for storage. Large-scale development of physical separation systems for CO_2 capture has not been completed. However, large-scale development of other commercial adsorption systems can be leveraged. Additionally, shipboard physical separation carbon capture systems will be much smaller than those envisioned for stationary power. Physical separation systems require a moderate amount of thermal energy and low amount of electrical power. Physical separation (adsorption) systems require a fairly complicated circuit of valves and piping for switching from adsorption to regeneration which is probably the biggest disadvantage. Systems have been proposed that use a rotating wheel of sorbent that has the potential to simplify the pipe and valving network. This concept has been used for decades in combustion air preheaters for stationary power plants as well as dehydration of low-pressure air, often for shipboard application by Munters Corporation.

Cryogenic separation capture systems have the unique characteristic of not requiring any solvent, sorbent, or membranes and totally rely on the thermodynamics in the flue gas stream to separate CO_2. This technology is fundamentally simple but does require a significant amount of electrical power for refrigeration. Challenges associated with heat recovery have not been demonstrated at large scale. However, this technology may have more opportunity on shipboard than for stationary power because of the smaller capacity system. Currently, the biggest disadvantage is the low level of maturity.

Oxy-fuel separation is in a somewhat different capture class. For shipboard capture, it would either require onboard generation of oxygen, or storage of oxygen generated on shore. Handling of oxygen also requires special consideration. Finally, oxy-combustion diesel engines are only a concept at this time so this technology is not deemed feasible for shipboard application in the near future.

In conclusion, it is the opinion of the authors based on a qualitative comparison that the chemical absorption or physical separation (adsorption) systems currently have the most potential for successSince chemical absorption systems are the most commercially advanced, they have received the most focus on shipboard capture studies. However, the authors believe that physical separation (adsorption) has the most potential for shipboard application at this time. It is also believed that a study of physical separation (adsorption) systems versus chemical absorption systems will benefit the shipping community. The follow-on techno-economic analysis should provide quantitative comparisons between technologies to further justify this conclusion.

2.2 Carbon Storage

Carbon storage is the last part of the marine carbon capture system. However, it is discussed ahead of CO_2 packaging because the method of storage defines how the CO_2 is packaged. Unlike shoreside installations where direct underground sequestration, pipelines, or large storage tanks can be built with capture systems, marine capture systems require a different design perspective. Vessel stability, navigability, and draft are part of vessel design considerations. Often vessel operating plant design changes require re-thinking fuel quantity, ballasting, and even the amount of cargo that can be safely carried. Fuel quantity reductions can influence trip duration and bunkering strategies. Reductions in cargo carrying capacity equate to reduced revenue for the owner/operator. All of this has to be taken into consideration when considering carbon capture and storage onboard ship.

The chemistry of combustion dictates that for every pound of fuel consumed, a significant amount of air is also required to sustain the process. The net result is a combination of elements and compounds in the exhaust, including CO_2. Due to this chemical process, about three pounds of CO_2 (purified) are formed for every pound of fuel burned. See APPENDIX A-1 for this calculation. On a traditional marine vessel, fuel consumption means that the weight of the fuel used is considered during the voyage to ensure that stability and propulsion efficiency is maintained. If instead the CO_2 is captured and stored, then accommodation must be made for this additional weight – storage for three pounds of CO_2 is required for each pound of fuel consumed, and this weight must be included in the design.

Another important design consideration for CO_2 tanks is volume. This helps drive the CO_2 gas processing decision as well. Ships are mobile structures that are made up of a finite volume of enclosed space to permit them to float. All of the systems and components are designed to fit into the hull of the ship. For example, on most traditional ships fuel tanks are typically formed by the hull of the ship and frames and bulkheads. When considering alternate fuels or even carbon capture storage, the density and properties of the chemical needs to be considered since volume is a critical design consideration. Often to use alternative marine fuels like hydrogen or natural gas, the best means of storage may be to cryogenically liquefy them. In order to store them, special cryogenic tanks need to be installed. These tanks do not necessarily conform to the hull of the ship as traditional fuel tanks are designed. Therefore, when fitting these tanks on ships there are volumetric losses to consider in addition to the lower energy density of these fuels. Similarly, CO_2 storage tank design tradeoff analysis is essential. The decision of storage significantly influences the packaging equipment decision discussed in Section 2.3.

2.2.1 Carbon Dioxide (CO_2) Properties

CO_2 is a colorless and non-flammable gas at normal temperature and pressure. At atmospheric pressure, CO_2 becomes a solid at approximately minus 110ºF (-79ºC). Solid, frozen CO_2 is called "dry ice". Liquid CO_2 only forms at pressures higher than about 5 times the atmospheric pressure, which is 14.7 psi (1 bar). At atmospheric pressure, dry ice does not melt into a liquid form. Instead, it goes directly from a solid state to a gaseous state in a process called sublimation.

If the temperature and pressure are both increased to be at or above the critical point for CO_2, it can adopt properties midway between a gas and a liquid. More specifically, it behaves as a supercritical fluid above its critical temperature (87.8ºF) (31ºC) and critical pressure (1,070 psi) (72.8 bar) expanding to fill its container like a gas but with a density like that of a liquid.

In thermodynamics, a critical point is the end point of a phase equilibrium curve. The most prominent example is the liquid–vapor critical point, the end point of the pressure–temperature curve that designates conditions under which a liquid and its vapor can co-exist. At temperatures above approximately 31ºC, the gas cannot be liquefied by pressure alone. At temperatures above the CO_2 critical point of approximately 31ºC, the liquid/vapor phase boundary vanishes, and the CO_2 exists as a supercritical fluid. Figure 15 shows a pressure-temperature chart for CO_2 while Figure 16 shows a pressure-enthalpy chart for CO_2.[39]

[39] CO_2 Pressure-Temperature and Pressure-Enthalpy Charts retrieved from: https://www.chemicalogic.com.

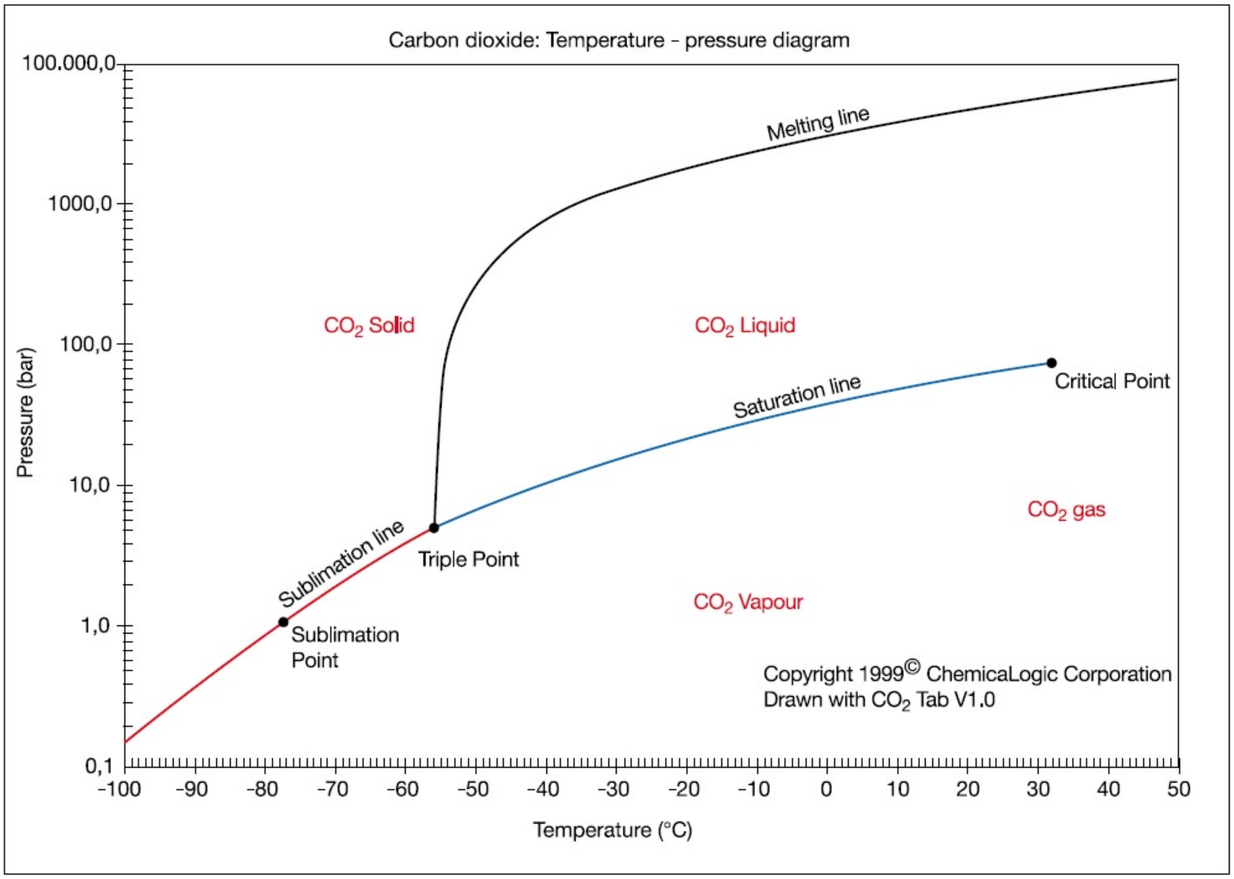

Figure AI.1 Phase diagram for CO_2. Copyright © 1999 ChemicaLogic Corporation, 99 South Bedford Street, Suite 207, Burlington, MA 01803 USA. All rights reserved.

Figure 15. CO_2 Pressure-Temperature Chart

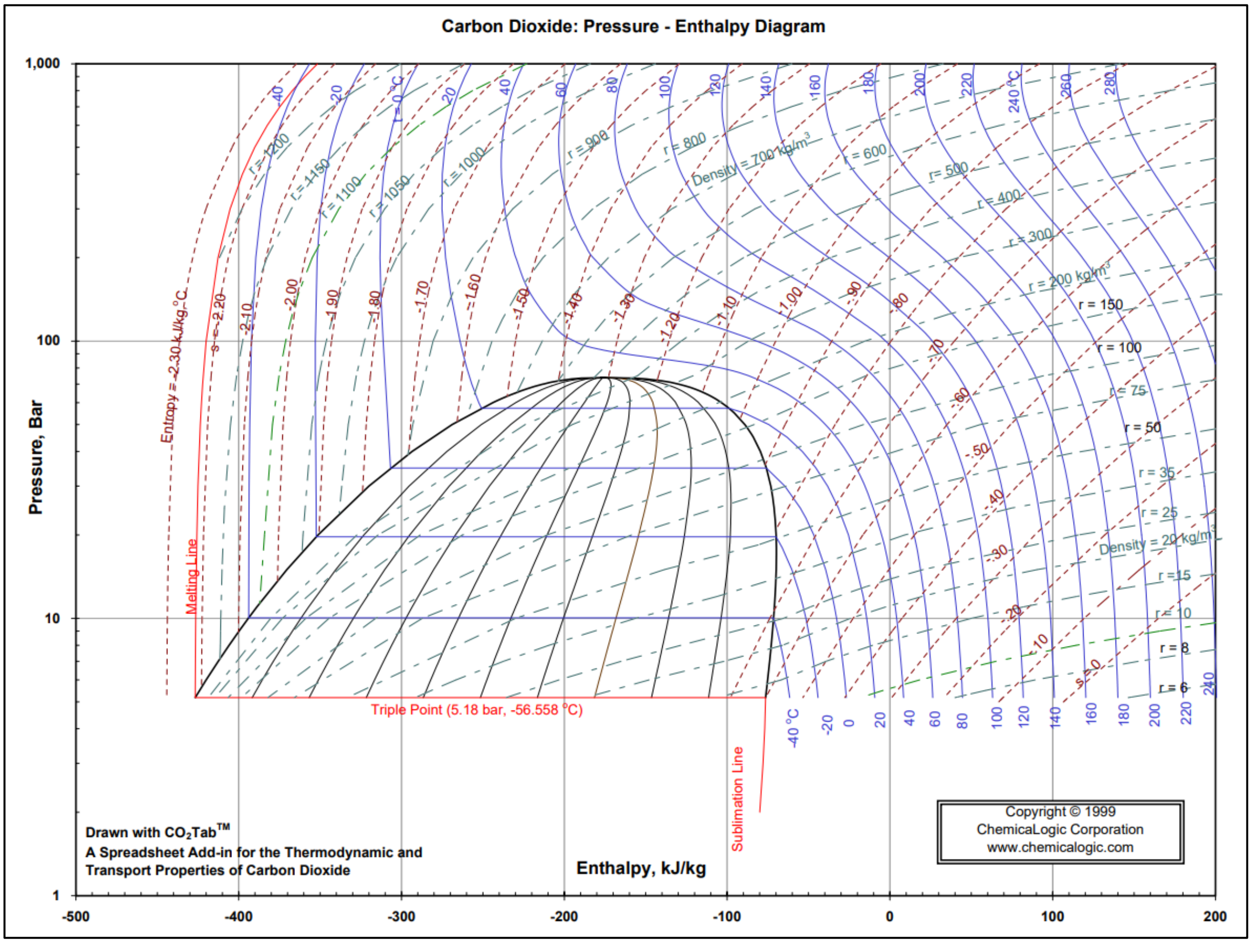

Figure 16. CO_2 Pressure-Enthalpy Chart

2.2.2 Carbon Dioxide (CO_2) Storage Methods

There are several practical ways to store CO_2. Each method has advantages and disadvantages. The space that the storage tank is located in is assumed to have a minimum temperature of 40ºF (4.5ºC) and a maximum temperature of 110ºF (43.3ºC) unless otherwise noted. The assumed space temperature is typical for ventilated spaces with no temperature control. CO_2 properties for each storage method are summarized below in Table 3.

2.2.2.1 Compressed and Refrigerated Liquid

CO_2 can be stored as a liquid as described in the section on CO_2 properties. Commercially, the storage conditions are typically around -10 to -30ºF (-23.3 to -34.4ºC) and 175 to 350 psi (11.9 to 23.8 bar). [40] For the purpose of this study, a conservative point of -20ºF (-28.9ºC) and 300 psi (20.4 bar) will be arbitrarily chosen. This provides margin between the storage point and the phase change conditions.

[40] Chart Industries. (n.d.). *Technical Manual: Carbon Dioxide Storage Tank Manual #11650869 Rev 1*. https://files.chartindustries.com/11650869_Carbon_Dioxide_Storage_Tank_Tech_Manual_Rev_I_ws.pdf.

CO_2 has a density at -20°F (-28.9°C) and 300 psi (20.4 bar) of 67.0 lbs/ft^3 (1,073 kg/m^3). The storage tanks and piping are heavily insulated to reduce heat transfer. Tank refrigeration is required to eliminate losses due to boiling and to ensure the CO_2 is maintained as a liquid. This method of storing CO_2 is relatively practical.

According to the manufacturer's data for the storage tank, approximately 0.08 percent of the refrigerated CO_2 tank's content will boil off daily, unless a separate refrigeration system is installed.

2.2.2.2 Compressed Gas at Ambient Temperature

CO_2 can be stored as a gas at high pressures. A typical storage pressure for CO_2 is around 800 psi (54.4 bar). The density of the stored gas is approximately 7.91 lbs/ft^3 (128 kg/m^3)at 110°F (43.3°C) (summer conditions), 57.2 lb/ft^3 (916 kg/m^3)at 40°F (4.4°C) (winter interior conditions), and 66.3 lb/ft^3 (1,062 kg/m^3) at -10°F (-23.3°C) (winter exterior conditions). As can be noted by the density change, the CO_2 at 800 psi (54.4 bar) changes from a gas to a liquid between 110 and 40°F (43.3 and 4.4°C) (the actual change is at about 65.1°F (18.4°C)). Because of the limited density, this storage method is not practical.

2.2.2.3 Compressed Fluid at Ambient Temperature

CO_2 can be stored as a compressed fluid at high pressures and room temperature. A typical storage pressure is around 3,000 psi (204 bar). The density of the stored fluid is approximately 51.7 lbs/ft^3 at 110°F (828 kg/m^3 at 43.3°C) (summer conditions), 62.8lb/ft^3 at 40°F (1,006 kg/m^3 at 4.4°C) (winter interior conditions), and 69.2 lb/ft^3 at -10°F (1,108 kg/m^3 at -23.3°C) (winter exterior conditions). This method of storing CO2 is relatively practical.

2.2.2.4 Dry Ice Storage at Ambient Pressure

CO_2 can be stored as a solid. At atmospheric pressure, CO_2 becomes a solid at approximately -110°F (-78.9°C). To store dry ice, a storage temperature of around -120°F (-84.4°C) is needed. The density of the dry ice is approximately 97.5 lbs/ft^3 (1,562 kg/m^3). This sort of storage will require a heavily insulated space and a cooling system to maintain the space temperature at approximately -120°F (-84.4°C). Additionally, appropriate equipment is required to transfer dry ice into the storage area, and to transfer the dry ice off the vessel. Material selection is limited for these extremely cold service temperatures. Further, transportation of dry ice for the pier will be a challenge, since it is not a typical method of transporting bulk CO_2. Because of these difficulties, dry ice storage does not appear to be promising as a method to store and bring CO_2 back to shore.

For seagoing vessels, there may be another answer using dry ice. A group working on a project led by Denmark-base Maritime Development Center is working on a concept to freeze CO_2 in exhaust and produce CO_2 dry ice cubes that are then released into the ocean and sink to the ocean bottom. Section 3.1.6 provides more details from this project.

2.2.2.5 Storage as an Absorbed Mixture or Mineral Carbonization

CO_2 can be stored using a sorbent to capture the gas. Commercially, it appears that the use of sorbent to store the CO_2 is not commonly practiced. The use of a sorbent is more commonly used to capture the

CO_2 from exhaust gases, with storage as a fluid.[41] Because sorbents are typically not used as a storage method, they will not be considered further.

The use of mineral carbonization is also technically feasible.[42] Calcium or magnesium silicates appear to be the most promising materials for mineral carbonization. The calcium or magnesium silicate required by weight is approximately 2.5 to 3 times the reacted carbon dioxide weight in this process. The equipment required for this storage method is also extensive, and because of excessive weight, this method will not be considered further.

Metal oxide frameworks have been studied as a CO_2 storage /capture method.[43] At the present time, they do not appear to be commercially available. This technology may become useful in coming years, but because they are not currently available, they will not be considered further in this report.

Table 3. CO_2 Properties at Various Storage Conditions

	Temperature	Pressure	Density
Compressed and Refrigerated Liquid	-20 °F (-28.9 °C)	300 psi (20.4 bar)	67 lb/ft^3 (1,073 kg/m^3)
Compressed Gas at Ambient Temperature	110 °F (43.3 °C) 40 °F (4.4 °C) -10 °F (-23.3 °C)	800 psi (54.4 bar) 800 psi (54.4 bar) 800 psi (54.4 bar)	7.91 lb/ft^3 (128 kg/m^3) 57.2 lb/ft^3 (916 kg/m^3) 66.3 lb/ft^3 (1,062 kg/m^3)
Compressed Fluid at Ambient Temperature	110 °F (43.3 °C) 40 °F (4.4 °C) -10 °F (-23.3 °C)	3000 psi (204 bar) 3000 psi (204 bar) 3000 psi (204 bar)	51.7 lb/ft^3 (828 kg/m^3) 62.8 lb/ft^3 1,006 kg/m^3) 69.2 lb/ft^3 (1,108 kg/m^3)
Dry Ice Storage at Ambient Pressure	-120 °F(-84.4 °C)	14.7 psia (1 bar absolute)	97.5 lb/ft^3 (1,562 kg/m^3)

[41] Mitsubishi Heavy Industries LTD. (2004). *Ship Transport of CO_2*. https://ieaghg.org/docs/General_Docs/Reports/PH4-30%20Ship%20Transport.pdf.

[42] Huijgen, J. J., & Comans, N. J. (2005). *Carbon dioxide sequestration by mineral carbonation. Literature Review update 2003–2004*. Energy research Centre of the Netherlands (ECN). https://www.osti.gov/etdeweb/biblio/20767421.

[43] Elhenawy, S. E. M., Khraisheh, M., AlMomani, F., & Walker, G. (2020). *Metal-Organic Frameworks as a Platform for CO_2 Capture and Chemical Processes: Adsorption, Membrane Separation, Catalytic-Conversion, and Electrochemical Reduction of CO2*. Catalysts, 10(11), 1293. MDPI AG. Retrieved from http://dx.doi.org/10.3390/catal10111293.

2.2.3 Carbon Dioxide (CO_2) Storage Method Evaluation

In order to understand which method is likely the best one for marine storage, a comparison can be made by developing CO_2 generation rates based on fuel consumption, and then using a vessel's operating profile to prepare a CO_2 storage requirement. Detailed calculations can be found in APPENDIX A Section 2.2.3.1 provides an estimate for the production of CO_2 based on three vessel types – an inland waterways harbor vessel, an inland waterways line haul towboat, and an ocean-going vessel of about 20,000 hp (14,900 kW). 20,000 hp for an ocean-going vessel with a single low-speed diesel engine is typical for a cargo ship of about 30,000 dead weight tonnes, and a speed of about 18 knots.

2.2.3.1 Carbon Dioxide (CO_2) Production

Most of the carbon dioxide produced by a vessel while underway comes from the internal combustion engine(s). For this document, three different scenarios are used for comparison purposes and operational assumptions are made to calculate CO_2 emissions.

Scenario 1 – Harbor Tug - The first scenario is a harbor tug that can readily offload captured CO_2 as it stays around its homeport assembling barge for tows, moving single barges, and idling between tasks. This vessel is assumed to have a total of 1,000 horsepower (hp). The vessel's engines operate on average at 50% maximum continuous rating (MCR) for a 12-hour day. The vessel will offload stored CO_2 once a week assuming its homeport has the infrastructure to accept the captured CO_2.

Scenario 2 – Large Towboat - The second scenario is a large towboat in the river trade that will have more problems offloading captured CO_2 since it normally does not stay close to its homeport. This vessel is assumed to have a total of 4,000 hp and have engines operating at an average of 80% MCR for a 24 hour day. The vessel will offload captured CO_2 every two weeks assuming its traveled route has the infrastructure to accept the captured CO_2 every two weeks.

Scenario 3 – Ocean-going Vessel - The third scenario is a large ocean-going vessel in international trade and will probably have the most trouble offloading its captured CO_2 as it travels worldwide and may not stay on the same trade route. This vessel is assumed to have a total of 20,000 hp and have engines operating at an average of 80% MCR for a 24 hour day. The vessel will offload captured CO_2 every four weeks assuming its traveled route(s) have the infrastructure to accept the captured CO_2 every four weeks.

APPENDIX A-1 of this document provides the calculation of the carbon dioxide generated per pound of fuel burned in diesel engines. APPENDIX A-2 approximates the fuel consumption for each operating scenario. APPENDIX A-3 documents several different storage technologies and the storage impact on the vessel. APPENDIX A-5 contains excerpts from the U.S. Code of Federal Regulations and American Bureau of Shipping (ABS) Marine Vessel Rules that pertain to carbon dioxide storage and transportation.

The CO_2 generation is estimated using the calculated fuel consumption based on the operating tempo for each scenario times 3.1 lb_{CO2}/lb_{fuel}. The calculations are shown in APPENDIX A-2. Table 4 provides the calculated fuel consumptions for each scenario.

Table 4. CO_2 Production Calculations

Scenario	Days Storage Required	Fuel Consumption (lbs)	CO_2 Generation (lbs)
1 – Harbor Vessel	7	15,805	48,995
2 – Large Towboat	14	364,160	1,128,900
3 – Ocean-going Ship	28	2,865,620	8,883,420

The actual CO_2 storage required is the CO_2 production times the capture efficiency. As discussed in Section 2.1, the capture efficiency of the carbon capture system can vary, but the likely systems will be work in the range of 80 to 90% capture. As a conservative assessment and to provide some margin, the storage sizing discussed in Section 2.2.3.2 will be based on 100% capture of CO_2. This oversizes the storage equipment by approximately 10 to 20 percent.

2.2.3.2 Carbon Dioxide (CO_2) Storage System Analysis

The three most practical storage methods discussed in Section 2.2.2 were evaluated using the CO_2 production numbers shown in Table 4. Detailed calculations are found in APPENDIX A-3. Weight and deck area for each method evaluated are shown in Table 5. Weight and total deck area required were the attributes chosen for comparative analysis. The weight and deck area requirements were calculated using candidate storage systems identified and currently available for this analysis and have not been optimized. The weight includes the CO_2 and the storage tanks required. The deck area requirement is developed from the dimension of the tank choice for the storage method. All assumptions are provided in APPENDIX A-3.

Table 5. Storage Requirements by Scenario

Scenario	Storage Method	Weight (Long Ton)	Deck Area Requirement (ft^2)
1 – Harbor Vessel	Compressed and Refrigerated Liquid Storage	82.7	780
	Compressed Gas Storage at Ambient Temperature	404.4	2,754
	Compressed Fluid at Ambient Temperature	85.6	612
2 – Large Towboat	Compressed and Refrigerated Liquid Storage	1,700	15,340
	Compressed Gas Storage at Ambient Temperature	9,025	61,500
	Compressed Fluid At Ambient Temperature	1,821.5	9,486
3 – Ocean-going Ship	Compressed and Refrigerated Liquid Storage	13,286	119,340
	Compressed Gas Storage Ambient Temperature	71,009	482.868
	Compressed Fluid At Ambient Temperature	14,251	74,052

Based on these calculations, compressed refrigerated storage will likely be the preferred method of storage if the tank size is optimized. This method can provide the lowest weight alternative (CO_2 and tank) and smallest deck footprint. The boil-off rate for each compressed and refrigerated tank is 0.08% of the tank contents if the tank refrigeration is provided by boil-off. For each tank, this amounts to approximately 15.5 pounds per day (7 kg/day). If a separate refrigeration system is provided, the boil-off rate will be zero.

The compressed fluid at 3,000 psi should be considered as a viable alternative. This conclusion will influence the method of carbon packaging as discussed in Section 2.3.

2.2.3.3 Carbon Dioxide (CO_2) Offloading

Another aspect that needs to be considered as part of the carbon storage system is the discharge system. As a vessel transits and captures CO_2, the CO_2 will need to be offloaded to make room for more CO_2. The timing for offloading the CO_2 will be a function of the system design based on operational requirements and periods of port visits. Vessels that stay in harbors, close to shore, or work as ferries have the most opportunity for offloading CO_2 and therefore the tanks can be sized for more frequent offloads. A large part of the differences in weight and deck area requirements shown in Table 5 can be attributed to the duration of the trip before the CO_2 can be offloaded.

Discharging either high pressure (3000 psi) or liquefied and refrigerated carbon dioxide is relatively straightforward using good piping practice. Compressed gas offloading will require high-pressure hoses and connections. However, in both cases, over-the-water offloading should be perfectly safe to the environment and to personnel provided basic safety procedures are followed.

Offloading either dry ice or solids containing carbon dioxide is significantly more challenging than dealing with fluids, especially considering that it will have to occur in port concurrent with cargo handling. In all cases, carbon dioxide handling will require special training and practices to prevent spills and/or accidents. On the subject of spills, however, the accidental release of CO_2 to the atmosphere is not dangerous to personnel unless it is in a confined space.

2.3 Carbon Packaging

Carbon packaging is the term used to describe the preparation of the CO_2 that is captured by the carbon capture system before it goes into storage tanks. As discussed in Section 2.1, there are different technologies that can be used to capture carbon. Each method has its own specific characteristics for the CO_2 that is captured.

The requirement for the quality of CO_2 is driven by the shoreside reuse or sequestration requirements. Quality of CO_2 is defined by purity. Purity is the amount of other gas collected in addition to the CO_2. The higher the purity, the purer the CO_2. Each capture method has specific capture rate percentages and ranges over plant operation. Regardless of the percentage of carbon captured by a specific type of system, it all typically shares the same level of purity. Typically, a 99% purity for CO_2 is required to move it in the current shoreside CO_2 transport infrastructure.

Things like water vapor, nitrogen, and other exhaust gas constituents, if left in the mix with the captured CO_2, can create problems for the storage tanks and increase the weight of what is stored. These impurities can also change the storage pressure and temperatures. Section 2.2 discussed the various methods to store CO_2 and concluded that for vessels, pressurized refrigerated storage would likely be the best method for shipboard storage.

2.3.1 Review of the Purity and Packaging Requirements for each Carbon Capture Method

Assuming that shipboard storage will cryogenically store CO_2 at -20°F (-29.8°C) and 300 psig (20.7 bar) pressure, the processing equipment needs to be designed to, in some cases, purify the CO_2 stream and to liquefy and compress it. For other methods, further CO_2 purification is required. Table 6 details the anticipated additional equipment that will need to be added to prepare the CO_2 for storage in the tanks.

Table 6. Anticipated Packaging Requirements for Various CC Methods

Carbon Capture Method	Capture Rate (%)	Purity Level Prior to Post-Capture Processing(%)	Likely Post-Capture Equipment Required
Chemical Absorption	90+	95	Dehydration, compression, liquefaction
Membrane Separation	60-85	85 – 90	CO_2 purification, compressions, liquefaction
Physical Separation (Adsorption)	90+	99	Compression, liquefaction
Cryogenic Separation	90+	99	Compression, liquefaction
Oxy-Fuel Separation	90+	94	Dehydration, CO_2 purification, compressions, liquefaction

The anticipated equipment required for each element of packaging include:

- Dehydrators – Dehydrators, frequently called dryers, are used to remove water vapor from a gas stream. For pressure dew points below -20°F, at 300 psig required for the recommended ship storage, the moisture concentration of the CO_2 must be reduced to below 20 ppm_V. To achieve this low level of moisture concentration, solid adsorbent dryers (compressed air) or glycol dryers (compressed natural gas) are commonly used. For shipboard applications, a solid adsorbent dryer is recommended. These dryers are dual tower regenerative dryers with one tower drying the CO_2 while the other tower is being regenerated. Either thermal swing or pressure swing regeneration can be used with pressure swing more common for 'small' dryers and thermal swing for a larger dryer. A recommendation on the specific dryer type will be made during the techno-economic analysis (TEA) phase of this project.
- Compressors – Gas compression units are required to take the CO_2 gas and pressurize to facilitate liquefaction. The type of compressor is commonly used for compression of compressed air.
- Refrigeration – Refrigeration systems are commercially available for cooling and condensing the the CO_2 product stream. Ships fueled with LNG can use the cooling capacity of the fuel as it is being used. The TEA planned for this study will focus on a ship using liquid fuel and thus this will not be an option. However, the refrigeration system can also be used to cool a circulation stream of liquid CO_2 in the storage tanks to keep the tanks chilled (if required).
- Gas Purifiers – The two capture processes that require purification are membrane and oxy-fuel separation, to increase purity of the CO_2 to be stored to 99%. Purification processes use a distillation column to remove the light ends (nitrogen, water, SO_2, etc) that may be present on

the CO_2 product stream. It is possible to integrate the purification with the liquefaction process to reduce the capital and operating cost compared to two independent systems.

Efficient packaging plant design is essential and needs to be matched with vessel operations and the capture technology chosen. These plants will not only have a volume and weight impact on the ship, but they also will require additional electrical power, which in turn creates more CO_2 to add power to the generator load. Section 2.3.2 discusses the power requirements for the packaging process.

2.3.2 Shipboard Energy Requirements for Liquid Storage of CO_2

The most promising storage method appears to be storage as a liquid at around 300 psig. Storage as a liquid requires the least deck space and adds the least weight. This storage method requires a refrigeration system to maintain the carbon dioxide at around -20°F.

Table 7 provides the estimated energy requirements, for liquid storage, for each vessel type and includes compression, liquefaction and storage costs. APPENDIX A-4 provides the calculations used to develop the estimated energy requirements. This is one of the areas that makes CO_2 capture and storage on an LNG tanker more attractive since LNG would be available to assist in the liquefaction and reducing energy requirements.

For the harbor vessel and towboat cases, the amount of power required for CO_2 packaging will likely require running another generator, which will result in generating additional CO_2 that must be captured as well.

Table 7. Compressed/Refrigerated CO_2: Energy Requirement Summary

	Harbor Towboat	Large River Boat	Ocean-going Vessel
CO_2 Compression	55 kW	200 kW	600 kW
CO_2 Liquefaction	35 kW	128 kW	475 kW
CO_2 Storage	0.75 kW	4.5 kW	102 kW
Total	*91 kW*	*333 kW*	*1,177 kW*

3 Marine Demonstration Projects and Technical Studies.

Section 1 discusses the current demonstration projects as well as recent technical studies focused on shipboard CSS. There is a lot of interest in CCS technology as a means to help with reducing CO_2 emissions. While CCS technology is often seen as short-term bridge technology until renewable fuel alternatives are available in great supply, others view CCS as part of the solution for meeting IMO GHG reduction objectives.

Some in the marine industry have articulated the need to keep all of the GHG emission reduction options on the table for consideration, including CCS. Leadership of Scorpio Tankers have recently partnered with a carbon capture technology company because of the continuing questions regarding application of alternative fuels and expressed the belief that carbon capture creates a viable path to decarbonization.[44]

In another case, a fleet manager at Solvang expressed concern for competition for e-fuels from other business sectors causing shipping to seek other fuels. By applying CCS as a bridge to a decarbonized future, GHG reduction can be started within a few years and the captured CO_2 could be used as a feedstock (carbon molecule) during production of electro-fuels (e-fuels). [45]

As described in the technology sections, U.S. DOE is funding carbon capture technology development for shoreside industry to capture GHG from traditional processes and enabling continued use of traditional fossil fuels while reducing their emissions. This development will also benefit the marine industry and future implementation of CCS. Current CCS demonstration projects are already adapting this shoreside technology to help with early testing and are showing promise. In addition to demonstration and pilot project summaries, a summary of research programs specific to CCS is also included in this section.

3.1 Demonstration Projects

Demonstration and pilot projects are very important to the investigation and technology assessment of the viability of CCS as an option for reducing GHG emissions. The good news is that there are a few demonstration projects that have started and more being planned. This section provides a brief description and references for some of the ongoing project and developments currently happening in the marine industry.

[44] *Scorpio Tankers Joins Efforts to Develop Shipboard Carbon Capture*. (2022). The Maritime Executive. https://maritime-executive.com/article/scorpio-tankers-joins-efforts-to-develop-shipboard-carbon-capture

[45] Blenkey, N. (2022). *Solvang sees CCS and HFO as Shipping's Greenest Option*. Marine Log. https://www.marinelog.com/news/solvang-sees-ccs-and-hfo-as-shippings-greenest-option/.

3.1.1 Samsung Heavy Industries

3.1.1.1 Samsung Heavy Industries and Panasia Maritime CCS Development and Testing

Samsung Heavy Industries, in cooperation with Panasia, has developed and is testing a carbon capture and storage system that can provide an economical solution onboard a range of vessels.[46] The system, which was designed for conventionally fueled vessels, also applies to LNG. Samsung became the first company in Korea to receive an Approval in Principle from KR, the Korean classification society, for their carbon capture technology. They are currently testing the system shoreside, but plan to commercial and optimize it for LNG-powered ships by 2024.

3.1.1.2 Samsung Heavy Industries and BASF Collaboration on CCS Onboard Maritime Vessels

Samsung Heavy Industries, in coordination with BASF, have announced a feasibility assessment of CCS onboard vessels using BASF's Onboard Carbon Capture System (OCCS) blue technology for flue gas applications. [47]The assessment will include a study on the marinization of BASF's technology as well as an engineering design and construction of the unit. The study will also include an evaluation on the feasibility of installing the technology onboard vessels.

3.1.2 American Bureau of Shipping (ABS) and Texas A&M Qatar

In June 2022, ABS and Texas A&M Qatar announced they will work together on a joint project to study carbon capture technology at sea including the development of a model for CO_2 capture on an LNG vessel.[48] They will also be studying the effect of the transition of energy toward a hydrogen economy on processing, emission and shipping across Qatar as an energy exporter.

3.1.3 Alfa Laval /Japan's National Maritime Research Institute

In 2021, Alfa Laval and the Japanese shipowner association, National Maritime Research Institute (NMRI), announced that they had teamed up to install an Alfa Laval hybrid PureSOx scrubber.[49] A modified PureSOx scrubber was installed on a recently delivered ship and tested to see if the unit could capture CO_2 from the auxiliary engines in port. The modified scrubber was operated in a closed loop cycle and demonstrated that scrubber technology could remove carbon from ship exhaust.

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[46] *Samsung Wins Approval for Carbon Capture System for LNG-Fueled Vessels. (2022, January 27).* The Maritime Executive. https://maritime-executive.com/article/samsung-wins-approval-for-carbon-capture-system-for-lng-fueled-vessels

[47] Hayek, S. (2022) *Samsung Heavy Industries and BASF Collaborate on CCS Onboard Maritime Vessels.* Carbon Capture Technology World News: The Official Newsletter of the Carbon Capture Technology Expo. https://www.carboncapture-expo.com/industry_news/%EF%BF%BCsamsung-heavy-industries-and-basf-collaborate-on-ccs-onboard-maritime-vessels.

[48] *Texas A&M Qatar and ABS agree on landmark carbon capture joint study*. (2022). Business & Industry Connection Magazine. https://www.bicmagazine.com/departments/hse/texas-a-m-qatar-and-abs-agree-on-landmark-carbon-capture-joint-study/.

[49] *Project Shows Scrubbers Could Play a Role in Carbon Capture at Sea*. (2021). Marine Log. https://www.marinelog.com/legal-safety/environment/project-shows-scrubbers-could-play-a-role-in-carbon-capture-at-sea/.

3.1.4 CCShip Project

In 2021, the Carbon Capture and Storage (CCS) Ship (CCShip) project was initiated, including eight partners (such as SINTEF Ocean and Wartsila Moss AS), to develop new knowledge and technologies for GHG reduction solutions for marine transportation through the use of CO_2 capture and storage technologies.[50] Both near- and long-term CCS technology solutions will be developed as well as key factors influencing CCS potential. Both mature chemical absorption technologies and emerging technologies will be evaluated with factors such as ship type and size, cargo, impact on cargo carrying capacity, voyage distance and routes, engine types, and CO_2 capture rates. CCShip will develop a roadmap to identify key aspects of cost-effective CCS capture. The project is anticipated to conclude in 2025.

3.1.5 CC-Ocean Project - "K" Line Mitsubishi CO_2 Capture Demonstration

In 2020, "K" Line/Mitsubishi Shipbuilding retrofitted a CO_2 capture system onto a bulk carrier, *Corona Unity.* [51] The unit installed is based on Mitsubishi Heavy Industry carbon capture technology for industrial applications. The CO_2 capture system is based on a chemical absorption (solvent: amine) system scaled to capture 0.1 ton/day of CO_2. The test was scheduled to last 7 months and all of the CO_2 captured was going to be stored in bottles to evaluate in a laboratory onshore. Figure 17 shows the system as installed on the ship.[51] Figure 18 shows a 3-D model of the unit and the characteristics.[52] Figure 19 shows the system schematic.[52] After the initial 7 month testing, the unit was left in place for additional crew testing. The initial results included a purity of 99.9% of the CO_2 captured.

Figure 17. CC-Ocean Carbon Capture Demonstration Project

[50] *CCShip - Deploying Carbon Capture and Storage for ships to enable maritime CO_2 emission mitigation*. (2021). Sintef. https://www.sintef.no/en/projects/2021/ccship-deploying-carbon-capture-and-storage-for-ships-to-enable-maritime-CO2-emission-mitigation/.

[51] *World's First CO_2 Capture Plant Installed on Japanese Bulker.* (2021). The Maritime Executive. https://www.maritime-executive.com/article/world-s-first-co2-capture-plant-installed-on-japanese-bulker.

[52] Mitsubishi Shipbuilding Co., Ltd. (2021) *Overview of "CC-Ocean" Project*, https://www.nepia.com/overview-of-cc-ocean-project.

Conceptual drawing of the CO_2 recovery demo plant

Exhaust Flow Rate	abt. 65Nm3 wet/h
CO2 Capture Amount	abt. 0.1 ton/day (Captured CO2 will be compressed and bottled for laboratory examination.)
CO2 Capture Rate	abt. 65% (Due to mobile spec. 90% is technically possible)
Weight	abt. 5ton

Figure 18. CC-Ocean Concept Drawing and Characteristics

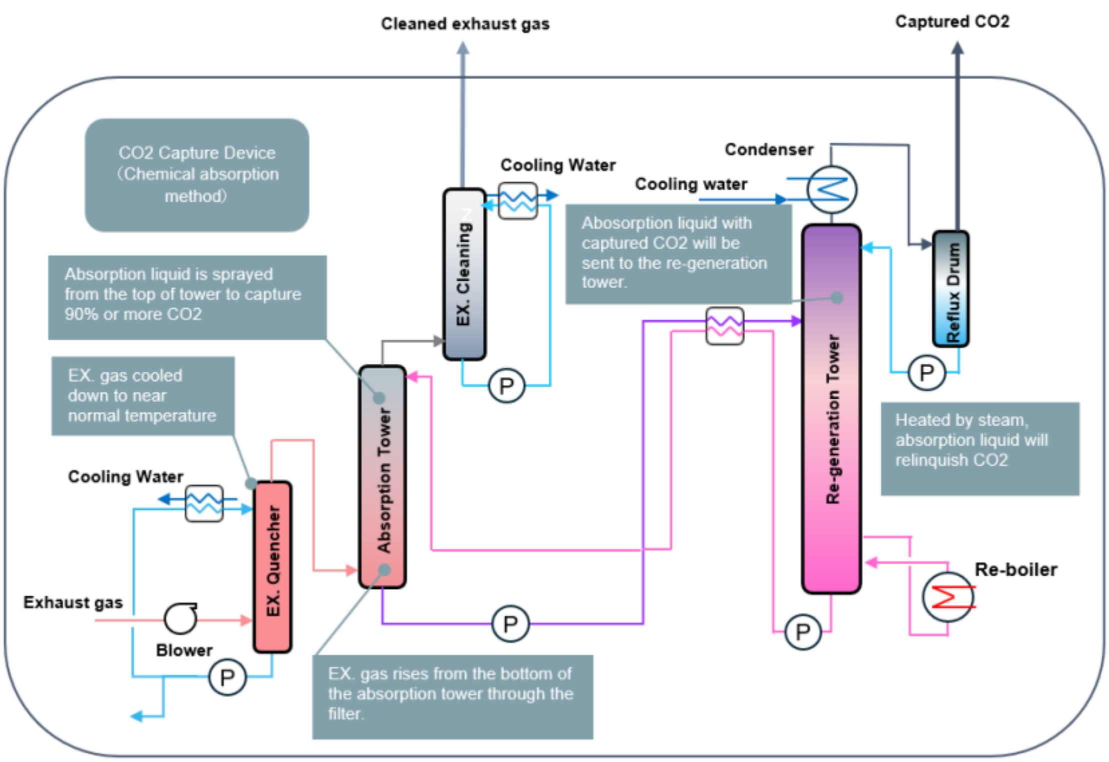

Figure 19. CC-Ocean CO_2 Capture System Schematic Diagram

3.1.6 decarbonICE™

Danish Maritime Development Center (MDC) has teamed with several shipping companies and shipbuilders to develop an onboard CCS solution that freezes the CO_2 from exhaust gas. [53] Once frozen,

[53] *DecarbonICE*. (2020). Cero2050. https://cero2050.es/en/decarbonice/.

the dry ice powder is made into blocks of dry ice and dumped into the sea. Since CO_2 is heavier than water, it will drift to the seafloor where it will penetrate the ocean bottom and be permanently stored as CO_2 hydrate. The objective of the project is to reduce CO_2 emissions from vessels by 90% by using the decarbonICE™ technology.

Using their on-board cryogenic plant, they will produce a Carbon Descent Vehicle (CDV) from CO_2 dry ice. The system will release the CO_2 dry ice blocks over large areas of the abyssal plain below 3,000 m deep. The dry ice penetrates the seabed sediment and is converted and stored permanently as CO_2 hydrate, of which trillions of tons already exist within the sediments of the seabed.

The project is anticipated to develop conceptual designs and proofs of concepts for selected vessels. Figure 20 shows a concept sketch.[53]

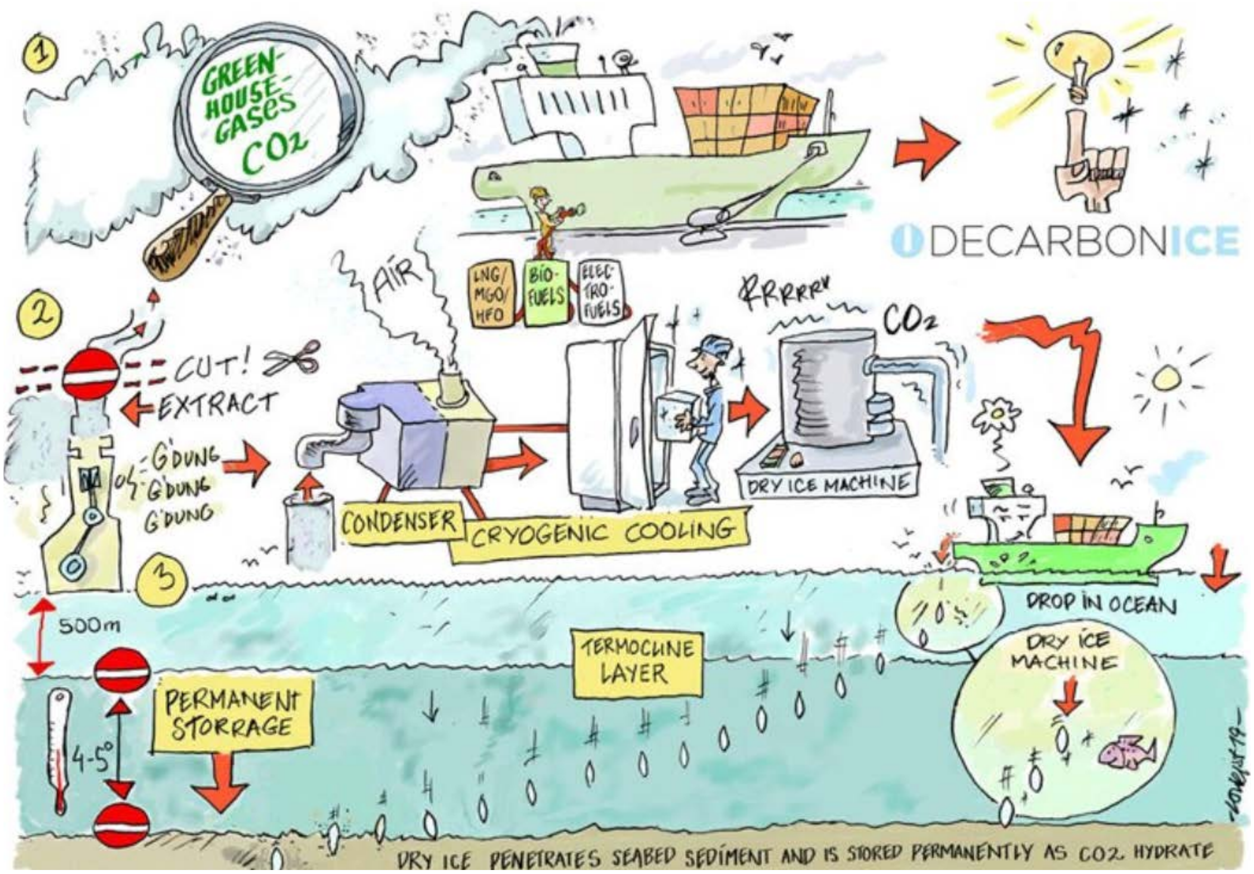

Figure 20. decarbonICE™ Concept Sketch

3.1.7 Carbon Ridge/Scorpio Tankers

In March 2022, Scorpio Tankers and Carbon Ridge developed an agreement to collaborate on the engineering, design, and validation of a small-scale test unit onboard one of the company's 120 product tanker vessels.[44] Carbon Ridge was started in 2021 and is designing a modular chemical absorption (solvent: monoethanolamine [MEA]) carbon capture and storage technology using existing gas separation technology and cryogenic CO_2 storage. Figure 21 schematically depicts the modular Carbon

Ridge CCS approach. [54] The design is intended to work within existing vessel design structures to reduce the amount of vessel modification required to integrate the technology.

Their design targets include low volume, highly modular components, reduced energy consumption and lower capital expenses for conversion.

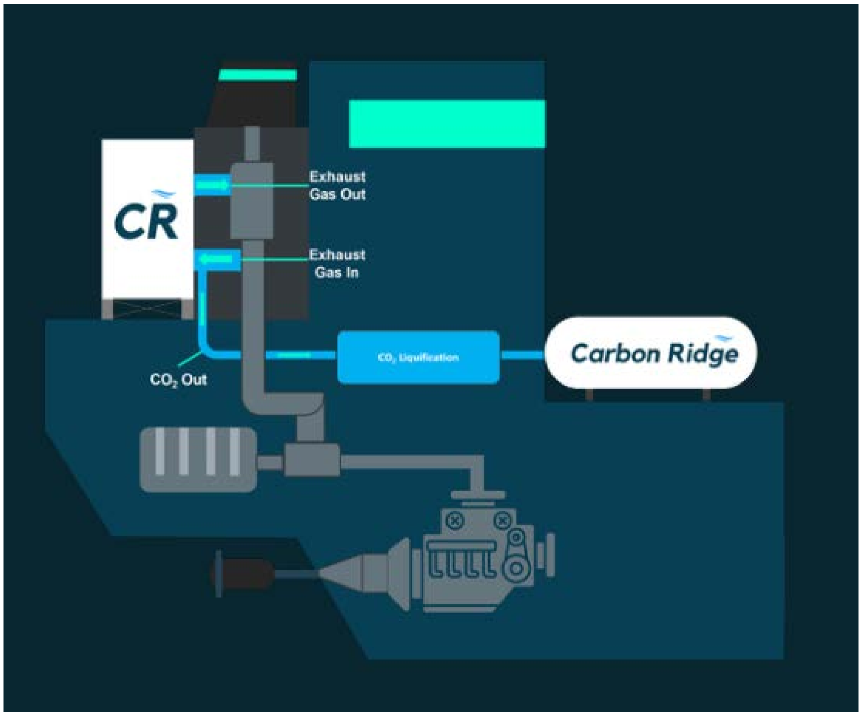

Figure 21. Carbon Ridge Modular OCCS System

3.1.8 Daewoo Shipbuilding and Marine Engineering CCS Development Program

Daewoo Shipbuilding and Marine Engineering (DSME) has teamed with GasLog and ABS to develop an onboard carbon capture system (OCCS) by the first quarter of 2023. [55] The system will be designed to capture CO_2 from engine exhaust onboard LNG carriers that DSME is building. The technology is based on using chemical absorption and mineral carbonation technology for shipboard storage.[56]

3.1.9 Langh Tech Carbon Capture

Langh Tech designs and supplies closed loop sulfur scrubber technology to the marine industry. [57] They announced the first successful tests onboard one of their sister company vessels – Langh Ship. Using

[54] *Carbon Ridge*. (n.d.). https://www.carbonridge.net/.
[55] *Daewoo Shipyard Leads Joint Development of Onboard Carbon Capture and Storage System for LNG Carriers*. (2022). Hellenic Shipping News. https://www.hellenicshippingnews.com/daewoo-shipyard-leads-joint-development-of-onboard-carbon-capture-and-storage-system-for-lng-carriers/.
[56] Bahtic, F. (2021). *DSME Develops Onboard CCS Technology*. Offshore Energy. https://www.offshore-energy.biz/dsme-develops-onboard-ccs-technology/.
[57] Prevljak, N. *Langh Tech Exploring Carbon Capture Onboard Ships*. (2021). Offshore Energy. https://www.offshore-energy.biz/langh-tech-exploring-carbon-capture-onboard-ships/.

their sulfur scrubbing system they were able to increase alkali to promote a reaction with CO_2 and alkali capturing CO_2 from the exhaust into the process water. They were limited to the maximum output of the installed alkali pump. At a main engine load of 85%, a 5% increased alkali dosing was able to achieve a 3.3% reduction of CO_2 emission. At 40% load, 7% CO_2 reduction was achieved. In addition to working to increase CO_2 capture, Langh Tech is evaluating ways to remove the captured CO_2 from the process water and shipboard storage.

3.1.10 Solvang/Wartsila

Solvang is a Norwegian ship operator and exhaust gas treatment company that has teamed up with Wartsila to demonstrate carbon capture.[45] Over the past 20 years, Solvang has been providing exhaust gas cleanup for heavy fuel oil (HFO) with LPG, LNG and biofuels. Through application of CCS technology, Solvang believes that HFO becomes the “climate winner” among other fossil fuels because its well-to-wake life cycle is lower than other fossil fuels including LNG, due to methane slip which has 25 times more global warming potential as CO_2. From their perspective, CCS is something that can be done within a few years. Then, when enough green energy is available, a transition to using the captured CO_2 to produce green fuels will be available.

In late 2021, Solvang and Wartsila Exhaust Gas Treatment launched a collaborative test program. Lab testing is underway on a 1.2 MW (1,609 HP) engine at a Wartsila facility in Norway. The carbon capture system has already demonstrated a high purity with 60% capture rates at some engine loads. By 2023, the team expects to integrate a scaled-up version of a CCS system on the *CLIPPER EOS* 7 MW (9,387 HP) Wartsila engine. Figure 22 shows an artist concept of the CCS Solution.[45] Figure 23 shows the test facility at Wartsila that currently is demonstrating the CCS technology.[45] Figure 24 shows the system schematic.[45]

Figure 22. CLIPPER EOS CCS Concept

Figure 23. Wartsila CCS Test Facility

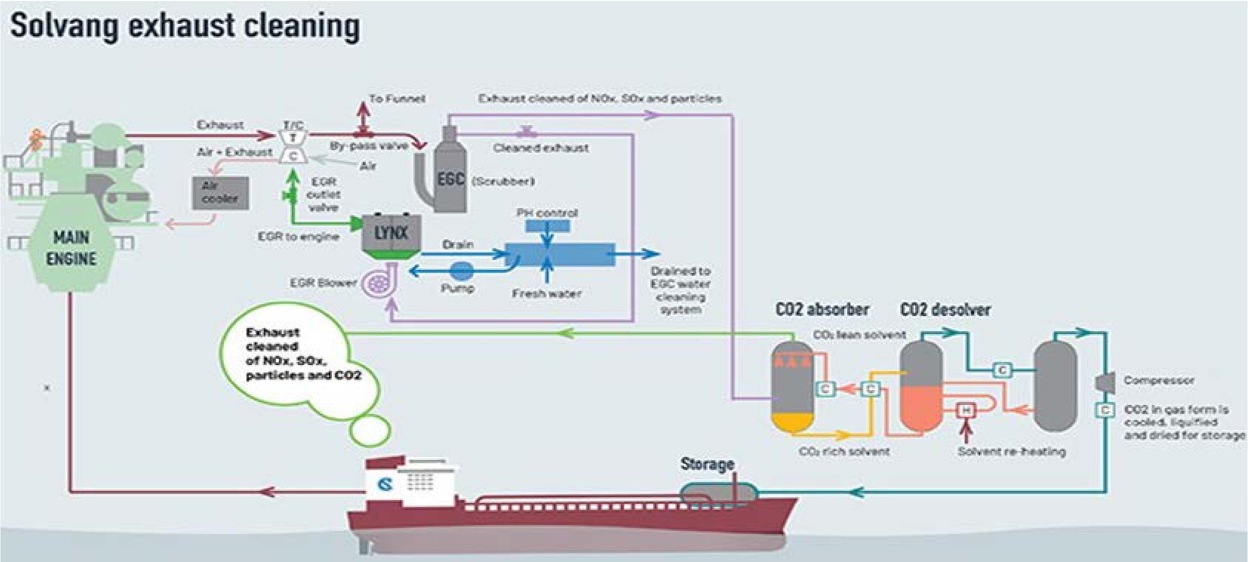

Figure 24. Solvang CCS System Schematic

3.1.11 X-Press Feeders Value Maritime Carbon Capture Demonstration Project

Value Maritime has been awarded a contract for two X-Press Feeders Group Vessels.[58] Value Maritime will install their carbon capture and clean loop system. They anticipate that once retrofitted in 2022, they will achieve 20% CO_2 emission reduction. Value Maritime's Carbon Capture Module is an add-on to their Filtree System which filters SOx and particulate matter.[59] In concert with the carbon capture module, they will be deploying their CO_2 Battery, which is their onboard CO_2 storage solution that is in modular form. The CO_2 battery will be removed from the ship, transported to CO_2 users, and then returned to the ship. In 2021, Value Maritime installed their first CO_2 capture module and CO_2 battery on the Visser Shipping's *Nordica*.[60]

3.2 Technical Studies

In recent years, there have been a number of papers and reports written on the subject of shipboard CCS. Six studies are presented here, which all concluded that insertion of marine carbon capture systems is technically feasible and in some cases economically comparable to other decarbonization strategies being considered.

[58] *Value Maritime to Install Carbon Capture on Two X-Press Feeders Ships*. (2022). Value Maritime. https://valuemaritime.com/news/value-maritime-to-install-carbon-capture-on-two-x-press-feeders-ships/.
[59] *Filtree System*. (n.d.). Value Maritime. https://valuemaritime.com/services/.
[60] *CO2 Capture and Storage to be Installed on Dutch Feeder Vessel*. (2021). The Maritime Executive. https://maritime-executive.com/article/co2-capture-and-storage-to-be-installed-on-dutch-feeder-vessel.

3.2.1 Carbon Capture Onboard LNG-Fueled Vessels

A noteworthy post-combustion carbon capture study was done as a Master's Thesis by J.T Van Den Akker.[61] Using a reference design vessel with a 3000 kW natural gas-fueled propulsion engine, a chemical absorption (solvent: amine) carbon capture system was conceptually designed and inserted into the vessel. The advantages of capturing CO_2 on an LNG-fueled ship include zero sulfur (which eliminates need for sulfur scrubbers), higher exhaust gas temperatures (which reduces the amount of additional heat for the absorption process) and the CO_2 liquefaction by the vaporization of LNG for the engine. Based on these advantages, the carbon capture system would have a very minimal electrical power requirement.

To accommodate the complete carbon capture and storage system, the vessel was lengthened by 6 meters and the exhaust stack required modification to permit the insertion of some of the columns required for the carbon separation. Location of the liquefaction system and the CO_2 storage tanks were designed to maintain ship stability, but also meant working around LNG fuel tanks.

The report concluded that only solid (dry ice) or liquid (cryogenic) were practical for storage of CO_2 on a ship. Solid storage, while possible, poses significant design challenges in both handling and tank design. Liquid storage was concluded to be advantageous because of the ability to use pumps to move the CO_2. One point raised about liquid CO_2 storage tanks was whether empty LNG tanks could be re-purposed during a voyage for storage. If this is possible, it would help reduce capital costs and volume impacts on cargo capacity. Of course, several issues need to be technically evaluated before this is considered further, including the different solid, liquid, gas temperature/pressure points between CO_2 and natural gas. LNG tanks would need to be empty and purged prior to use as CO_2 storage tanks, and an engineering analysis would need to be done to ensure the tank's support structure, as well as the tank itself, can withstand the higher density of CO_2 versus natural gas.

As noted previously, the choice of an LNG-fueled or LNG transport vessel provides both the heat from exhaust and cooling from evaporating LNG. This means that the only other energy required for the process comes from equipment required to run the plant. For example, since there is a pressure drop penalty (i.e. increased backpressure) on the engine from the absorption process, a fan is required in the exhaust stream to keep the engine backpressure in design range. Also, there are compressors and pumps required for the liquefaction and pumps to move it to the storage tanks.

Overall, the author concluded that shipboard carbon capture was technically feasible. This report developed a concept chemical absorption carbon capture system design, evaluated ship modification requirements, and determined economic performance based on assumed operating scenarios. Capture rates of up to 90% are feasible for main diesel engines. However, the smaller auxiliary diesel generators used in port or at anchor may not be able to use the same capture system which is sized and scaled for the main engine. Vessel type, engine type, and operating profiles can influence carbon capture performance and the impact on capital investment, which is the largest driver of system cost. Based on

[61] Van den Akker, J. T. (2017). *Carbon Capture Onboard LNG-Fueled Vessels: A Feasibility Study*. Delft University of Technology. https://repository.tudelft.nl/islandora/object/uuid%3Aa94741f3-c7cb-4970-80d1-bceebff4e423.

the model built in the thesis, the cost was estimated to be €74 per tonne CO_2 avoided. A primary driver to the cost on ships is that plant utilization is variable depending on the ship operations, as engine loads and equipment operation varies, which drive carbon capture rates and system performance. Additionally, unlike shoreside facilities, ships need to pay for shipboard CO_2 storage tanks.

3.2.2 CCS Energy Efficiency Design Index (EEDI) Impact

In a paper published in the International Journal of Greenhouse Gas Control in 2021, Marcin Stec, et al. evaluated the possibility of reducing a ship's IMO EEDI using a post-combustion carbon capture system.[62] The study evaluated the performance of a chemical absorption (solvent: amine) carbon capture system on an engine burning high sulfur content (3.5%) heavy fuel oil.

Three cases were run – arctic, ISO, and tropical conditions (as detailed below in Table 8) on a 47,000 DWT tanker with limited exhaust gas heat recovery. As CO_2 was captured by the system, SO_2 was also captured up to a rate of 95-98% with desulfurization equipment. CO_2 recovery ranged from 31.4 to 56.5% with ships operating in the tropics having more waste heat and a higher CO_2 recovery. Additional electrical power was required of between 498 to 786 kW depending upon the operating location.

Table 8. Ambient Conditions for CCS EEDI Impact Study

	Arctic	ISO Reference	Tropical
Air Temperature (^oC)	10	25	45
Seawater Temperature (^oC)	10	25	32
Relative Air Humidity (%)	60	30	60

The study also concluded that a low concentration of CO_2 in the exhaust gas leads to a subsequent lowering of CO_2 recovery. Through the use of a modified EEDI calculation (CCS is not formally included in the EEDI equation at this time), a ship equipped with a carbon capture system is calculated to have an EEDI value of 3.16 gCO_2/ton-nm in tropical conditions, which is half that of the same tanker without one. The study revealed that while operating in an arctic condition, the CO_2 captured is reduced and the electrical load required is also lower. In tropical conditions, both power required and CO_2 capture rates are increased.

The impact of energy required for CO_2 processing for storage was not discussed. This issue is one of the main reasons why EEDI and CCS are under development, since the extra energy requirement will deteriorate the EEDI calculation. Space or volume requirements of the carbon capture equipment was

[62] Marcin Stec, Adam Taturczuk, Tomasz Iluk, and Mateusz, (2021) *Reducing the Energy Efficiency Design Index for Ships Through a Post-Combustion Carbon Capture Process*, International Journal of Greenhouse Gas Control, 108.

also not discussed. However, the results are certainly positive for this technology as a mechanism to reduce CO_2 emissions in either a retrofit or new build situation.

3.2.3 CO_2ASTS – carbon capture, storage and transfer in shipping

This study evaluated post-combustion carbon capture and storage on LNG-fueled ships.[63] Carbon capture was accomplished by using chemical absorption (solvent: amine) and included onboard liquefaction and storage.

Three LNG-fueled ship cases were evaluated – a reference sea-river vessel (1,050 kW), a reference dredger (7,600 kW), and a reference cruise ship (36,000 kW). For each vessel, the use case was evaluated, a vessel layout was developed, and an economic feasibility was determined and included things like loss of cargo capacity. Sketches of the proposed alterations to the design or modifications to the current vessels are described as well as some operating details and CO_2 storage tank size requirements. Table 9 provides a comparison of system design and economic evaluation results provided in the report.

Table 9. Reference LNG-fueled Vessel Design Specifics

	Sea River Vessel	Dredger	Cruise Ship
System Design			
CO_2 Capture Rate [%]	75	54	69
Total Power Consumption [kW]	13	95.2	396
Amount of Cooling Water [m^3/h]	28.6	460	871
Total weight (including solvent and liquid CO_2) [ton]	97	371	1176
Storage Duration [Days]	14	6	7
Storage Tank Volume (based on storage duration) [m^3]	42	178	548
CO_2 Stored [ton]	46	187	585
Expected Power Consumption [GWh/year]	1.74	N/A	N/A
Economic Feasibility			
Revenue Loss [k€/annum]	25	100	550
Estimated CAPEX [M€]	2.67	5.85	13.32
Levelized Capture Cost [€/ton]	301	115	154

Based on the results of their evaluation for each use case, it appears that none of the levelized capture costs approach 50 €/ton of CO_2 captured. As seen in Table 9, capture rate, revenue loss, CAPEX, and capture cost are different for each size vessel with capture cost being the highest for the smallest vessel. This means that scale of plant likely matters for a variety of reasons including equipment cost and design

[63] Monteiro, J. (2020). *CO2ASTS – Carbon Capture, Storage and Transfer in Shipping*, INTERREG Deutschland Nederland.

requirements. Despite the higher capture rate for the river vessel, the CAPEX drove the capture cost to almost twice as much as the other cases.

The other interesting part of this study was a comparison of the results of their calculations with a 2017 LR document that discusses Zero Emission Vessels (ZEVs) and how the marine industry will get there.[64] Using the LR ZEV study results, to be competitive as an alternative, the CO_2 prices for the most-cost effective zero emission option was on the order of $250-300 per ton; ammonia and hydrogen were competitive at $500 per ton. While the carbon capture alternative is a less expensive alternative, it does not deliver 100% CO_2 emission reduction. In the short term, however, it showed that CO_2 capture technology may have a place in the marine industry.

3.2.4 Oil and Gas Climate Initiative and Stena Bulk Tanker Marine Carbon Capture Study

In 2021, Oil and Gas Climate Initiative (OGCI) and Stena Bulk conducted a feasibility study with ARAMCO to evaluate carbon capture to see if it is technically feasible and could play a long-term role in meeting IMO decarbonization targets.[18] Three ship types from Stena's fleet were considered for the study. A Suezmax Tanker was selected since it was believed to be the worst case technically, primarily due to very poor exhaust gas heat availability. The LNG carrier was evaluated to be the easiest to integrate a carbon capture system due to sufficient exhaust gas heat and the use of vaporization of LNG to liquefy the CO_2. The third vessel, a Medium-Range Tanker had a higher exhaust gas temperature. The team selected the worst-case scenario to help identify any potential issues. Their theory was that if it worked for this vessel, it will work with the others in their fleet.

A key part of the study was to evaluate the potential capture technologies including chemical absorption, adsorption, membrane separation and cryogenic separation. As discussed in Section 2.1, chemical absorption and cryogenic separation have similar performance in terms of CO_2 purity (99%) and carbon capture rate (90-99%). What separated them for the purposes of this study was the higher technology maturity level for chemical absorption since almost all of the current shoreside CCS projects use this technology. Therefore, chemical adsorption was selected as the technology and the study was based on using the ARAMCO CO_2 capture technology.

The Suezmax tanker has one 15.7 MW two-stroke diesel engine as its main propulsion engine and three 1MW diesel generators for hotel and auxiliary power and a boiler for crude oil transfer. The study evaluated the exhausts from each of these units. The carbon capture system requires both electrical power from the auxiliary engines and heat from the engines or boiler. Since the percentage of capture rate is dependent on both power and heat from the current plant operation, additional fuel consumption and additional CO_2 emissions may be generated to achieve it. Therefore, they termed the net CO_2 emissions reduction as gross emission reduction of the carbon capture system minus the amount of additional CO_2 emissions generated to perform the capture.

In addition to the capture system, a blower was added to the main propulsion engine exhaust to ensure there was no backpressure added to the engine to avoid performance penalties. After the exhaust was

[64] *Zero Emission Vessels 2030. How Do We Get There?* (2017). Lloyd's Register. https://www.lr.org/en/insights/global-marine-trends-2030/zero-emission-vessels-2030/.

flowed through the capture system, it was routed to a liquefaction system where it was compressed, liquefied, and stored in the insulated CO_2 tanks at a pressure of 16 to 20 bars. Two tanks of 750 m^3 capacity were installed on the top deck of the tanker where there was space available.

The impact of mass and volume of the inserted capture system was evaluated from both a space and stability standpoint. It was estimated that 2,500 t of DWT would be lost. For the Suezmax tanker, space was available on the top deck for the tanks. The tanks were designed for 50% capture rate and a 21-day voyage.

Safety concerns resulting from the Hazard Identification (HAZID) Analysis indicated that exposure to the amine solvent and concentrated CO_2 were deemed manageable through proper engineering and safety protocols. Additionally, any hazards from the cryogenic systems added to liquefy the CO_2 can be safely addressed following international guidelines for handling liquefied gases in bulk.

Based on the capture system design, a performance and economic analysis was undertaken. During the performance analysis, three capture rates were evaluated. For all cases, it was assumed that the tanker was operating at a set speed and with a main engine power of 75% maximum continuous rating (MCR). The three capture rates considered were 8%, 50%, and 90%. The 8% capture rate represented the estimated rate of capture that the system could produce with only the energy from the main propulsion engine exhaust gas heat energy and no other sources. Both the 50% and 90% case required additional heat energy provided by the auxiliary generator engines or boiler.

Figure 25 shows the results of the performance analysis.[18] The 8% case represents what is shown in the diagram as the reference vessel. It also shows the lack of CO_2 reduction impact but provides the reference case to calculate the effective emissions for the other two cases, which are termed the emission avoidance. Table 10 shows the additional fuel required to meet the capture rates of 50% and 90% as well as the “avoidance” or net CO_2 emission reduction rate after the impact of the additional CO_2 contributions from extra fuel being consumed to perform the capture.[65] To sustain a capture rate of 50% for the carbon capture system, a net of 40% reduced CO_2 is captured. Of course, this additional fuel consumed also increases the vessel operating expenses. A major point to keep in mind is that for a different type of vessel this performance may be different, and even improved, since this study chose the worst case vessel and more exhaust heat may be available on other engines.

[65] OGCI. (2022). *The Feasibility of Marine Carbon Capture* [Slides]. Oil and Gas Climate Initiative. OGCI Transport Workstream Presentation.

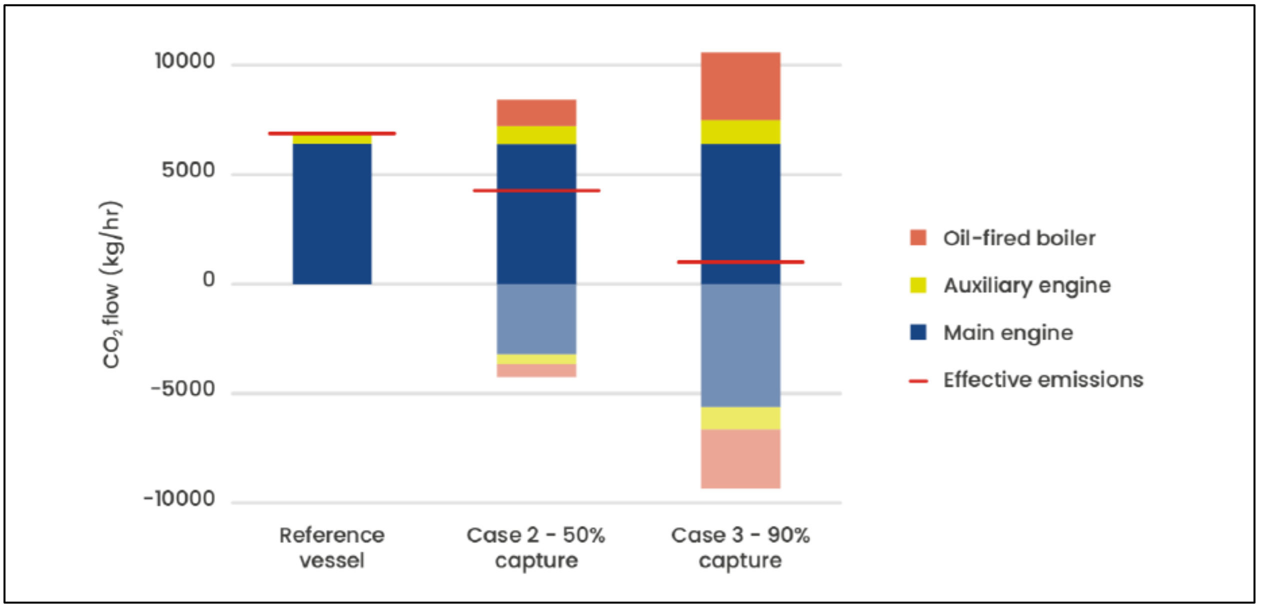

Figure 25. CO_2 Emission Comparison for 8%, 50%, and 90% Capture Rates

Table 10. Performance Summary for 8%, 50%, and 90% CO_2 Capture Cases

	Cases	Additional Fuel Needed to Generate Heat and Electricity	CO_2 Avoidance at 75% MCR
1	8% Capture (No Energy Input)	None	~10% (heat energy constrained)
2	50% Capture	22%	40%
3	90% Capture	52.7%	84%

The report also provided an economic analysis of the differences in capital expenditures (CAPEX) and operating expenditures (OPEX). For the 50% and 90% capture rate cases, the estimated CAPEX was 20.1 M€ and 28.2 M€, respectively. The OPEX (both fixed and variable) was estimated for the 50% and 90% case to be 938.4 k€ and 1,808.4 k€, respectively. No consideration or cost for the in-port infrastructure required to support this capture activity was included in the analysis.

Finally, an analysis was undertaken for meeting the IMO 2030 CO_2 reduction target of 20-30% below existing CO_2 emissions. Since the amount of heat required to run a 25% to 30% capture rate is less than the 50% or 90% case, the OPEX is reduced with amortized CAPEX and fixed OPEX become the largest part of the daily OPEX. Both a 12-year and 20-year remaining life analysis was done for the Suezmax ship retrofitted with the CO_2 capture system. Additionally, the study modeled varying levels of capture over the lifetime of the ship including a 30% capture rate for 100% use of the capture system during transit, 50% of the time during transit which reduces lifetime CO_2 capture from 30% to 15%, and a case where 50% of the transit time until 2025 and then 100% by 2030 which would provide a 20% lifetime capture. For the 30% carbon capture rate at 100% of transit time, the total investment over 12 years was estimated at $18.5 M. The other two cases were $17 M and $17.8M, respectively. Table 11 shows the results of the carbon costs on a $/t$CO_2$ captured basis. The study modeled the three capture cases for a 12-year and 20-year lifetime and then included a cost model for a 20-year period with subsidy of $35/t$CO_2$ and the same subsidy with an assumption of a 50% reduction in CAPEX. These results can be used to compare to alternative CO_2 reduction methodologies including low carbon and zero carbon fuels.

Table 11. Estimated Carbon Capture Cost

Cost Basis ($/t$CO_2$)	100% Use – 30% Capture [$/t$CO_2$]	50% Use (30% Capture rate – but lifetime 15% total capture) [$/t$CO_2$]	50% use until 2025 and increase to 100% by 2030 [$/t$CO_2$]
12 Year	175	297	232
20 Year	153	254	201
20 Year with Subsidy of $35/t$CO_2$	106	207	153
20 Year with Subsidy of $35/t$CO_2$ and 50% reduction in CAPEX	65	131	96

The study concluded that marine carbon capture is technically feasible with no major barriers even on one of the most challenging cases – a Suez tanker with a high efficiency two-stroke engine . Insertion will likely be easier on other types of vessels, since this was their worst case. While both CAPEX and OPEX are high with CAPEX driven primarily from the high costs of the liquefaction system, storage tanks, and the absorption column materials. Despite these costs, OCGI concluded that marine carbon capture can play a role in meeting IMO 2050 goals and is compatible with current carbon capture strategies worldwide. The next step for this team is to demonstrate this technology on a shipboard application.

3.2.5 Transport-Technology Research Innovation Grants Cryogenic Carbon Capture Study

In 2019, a study was performed by several organizations for the U.K. Department of Transport. The work centered around carbon capture as an alternative to the transition of zero carbon fuels.[66] Using

[66] Willson, P. (2020) *Evaluation of Marine Application of Advance Carbon Capture Technology*, Transport Technology Research Innovation Grants (T-TRIG), Final v1.1.

the cryogenic carbon capture system developed by PMW Technology, the team evaluated capture and storage at sea and then delivery to ports for carbon sequestration.

Frontier Economics had completed a study for the Department of Transport to examine the economics of decarbonization through zero carbon fuels.[67] Their study concluded that the cost of carbon abatement was around £180/ton CO_2 equivalent for ammonia. The cost analysis developed for the T-TRIG carbon capture study was evaluated on the same cost basis as the Frontier Economic study.

Two cases were studied in this Transport-Technology Research Innovation Grant (T-TRIG) report: 1) an LNG-fuelled 10,200 tonne car and truck carrier, SIEM CONFUSIUS and 2) a hybrid diesel-electric 830 tonne ferry, VICTORIA OF WIGHT. Aspects evaluated included the feasibility of the cryogenic system and carbon storage insertion, impacts to vessel stability, and CAPEX and OPEX. In addition to the shipboard application and operation, this study also looked at estimating the costs for the shoreside CO_2 receiving facilities as well as the sequestration costs.

The cryogenic carbon capture process developed and patented by PMT Technology in 2016, known as the Advanced Cryogenic Carbon Capture (A3C) process. It was developed for exhaust gas carbon capture of gas streams containing 1.5% to 40% mol CO_2. Marine diesel engine exhaust gas typically ranges between 3.5 to 6% carbon dioxide. The A3C process freezes the CO_2 out of the exhaust stream and has a capture rate of over 90% and up to 99%. As shown in Figure 26, the process works in two stages.[66] The first stage cools the exhaust and dehydrates the exhaust gas and the second stage cools the exhaust to pull the CO_2 out as frost coating on a moving bed of material. The captured CO_2 frost melts and delivers gaseous CO_2 to the liquefaction system before being cryogenically stored in a storage tank. Figure 27 shows the complete carbon capture and storage system.[66] Per PMW, this A3C process is at Technology Readiness Level (TRL) 3-4 as it was evaluated. It was estimated to be up to 70% lower cost for capture than the amine process. Their next step in the system development is a scale unit laboratory test.

[67] Bell, M., Deyes, K., et al. *Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution – Scenario Analysis: Take-up of Emission Reduction Options and their Impact on Emissions and Costs – A Report for the Department for Transport, Frontier Economics*, (2019) UMAS, E4tech and CE Delft.

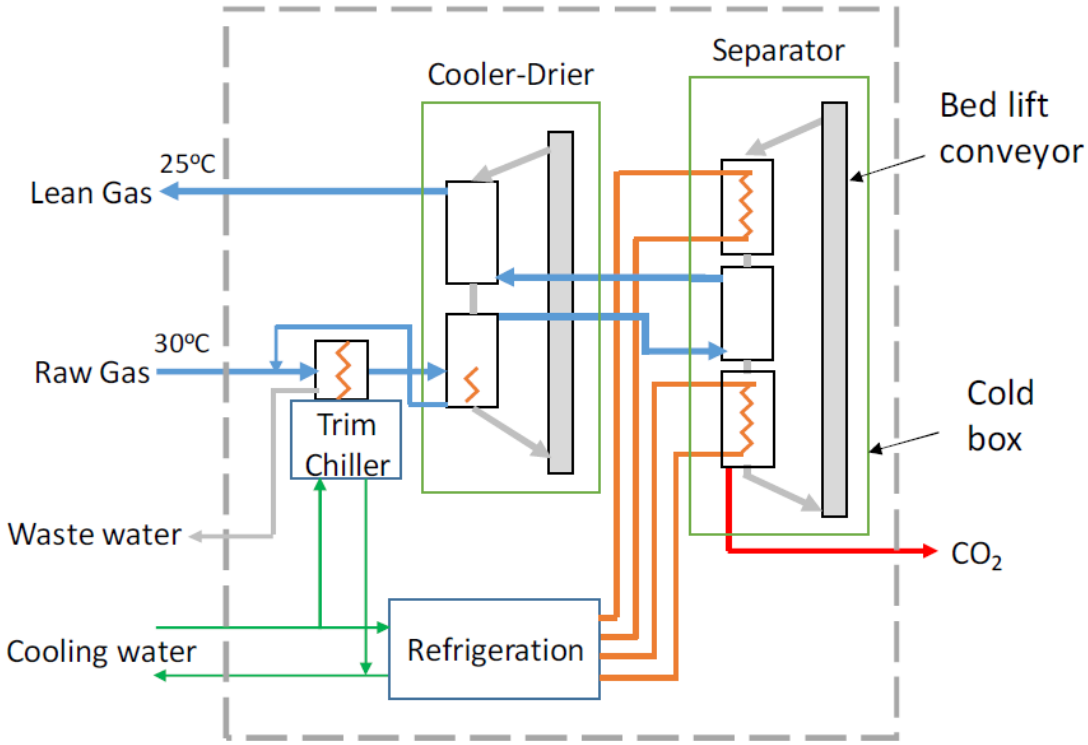

Figure 26. A3C Separation Process

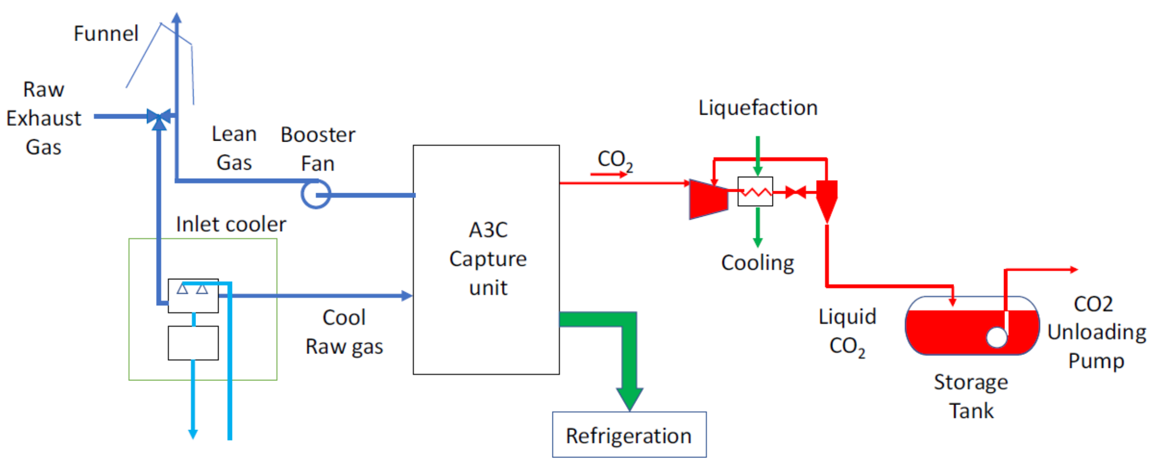

Figure 27. A3C Marine Application Configuration

Multiple cases were run for the SIEM CONFUSIUS including both LNG and MGO cases while only two cases were run for the VICTORIA OF WIGHT. The design concepts and configurations are different for each vessel because of the size and propulsion plant configurations. Table 12 shows the levelized cost of capture on a per tonne of CO_2 basis. When compared to the Frontier Economics study for costs of carbon abatement, which was £180/tonne of CO_2, insertion of A3C cryogenic system is about 50 percent of the levelized cost using the same methodology.

Table 12. Cryogenic Carbon Capture Levelized Cost of Capture

Vessel	Annualized CAPEX [£k]	OPEX [£k]	Carbon Captured [CO_2/y]	Levelized Cost of Capture [£/tonne CO_2]
SIEM CONFUSIUS	814-1,440	1,152-2,205	26,654-54,490	63.4-82.3
VICTORIA OF WIGHT	433.1	332	8,316	93.07

Some other noteworthy parts of the assessment included an evaluation of the tankage required for carbon storage. As noted previously, the addition of these tanks can affect the amount of cargo space available. Another approach discussed was to reduce the range of the ship, which is done by reducing the amount of fuel carried to allow for the additional weight added by CO_2 storage. For the VICTORIA OF WIGHT ferry, a single tank with 15 hours of sailing capacity could be used. Specifically a 20-foot T75 ISO Cryogenic tank container could be used and swapped out with an empty one once a day.

Additionally, the study points out that additional fuel is consumed because of the cryogenic system power demands. When operating at a 90% capture rate they estimated about 17% more LNG consumption or 24% for MGO. Even with the additional fuel costs, the study concluded that this system is technically feasible for shipboard application and should be very easily integrated with either existing CO_2 shoreside facilities or future ones in major ports. When including both vessel and shoreside costs into the project, they estimated levelized cost of capture and storage to be between £85 and £120/tonne CO_2.

3.2.6 HyMethShip Concept

A carbon circulation concept was developed through a cooperative research and development project funded by the European Union's Horizon 2020.[68] The idea behind carbon circulation is that once CO_2 is emitted once and captured, it can be continuously reused to form methanol via methanol synthesis (CO_2 and H_2 as feedstocks). In this case, the captured CO_2 is used to produce methanol that is reused shipboard, with the CO_2 being re-captured and sent to make the methanol fuel again, thus creating a circular carbon process. Figure 28 shows the proposed plant concept.[68] The process uses e-methanol (based on hydrogen produced from electrolysis of H_2O using renewable sourced electricity) as the source of fuel that is stored shipboard. This concept uses pre-combustion CO_2 capture to produce hydrogen for shipboard energy conversion use. The captured and stored CO_2 is then offloaded and sent to an e-methanol production facility ashore.

[68] Dr. Nicole Wermuth, DI Marcel Lackner, DI Dieter Marnstedt, et al., (2020) *The HyMethShip Project: Innovative Emission Free Propulsion for Maritime Applications*.

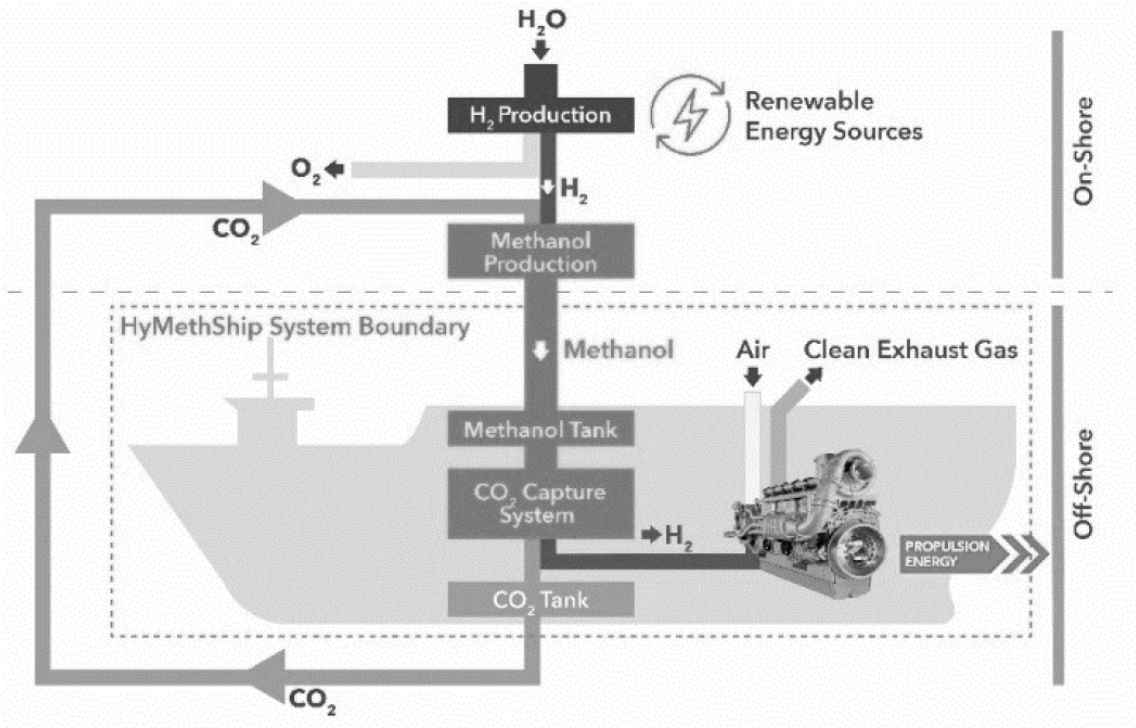

Figure 28. HyMethShip Concept

The project was started in 2018 and ended in June 2021.[68] The paper describes the life cycle analysis of the HyMethShip concept versus a ship operating on MGO. Additional research was also conducted that centered around conversion of traditional diesel engines to use methanol-hydrogen as a fuel.

3.2.7 Seabound

Calcium looping technology is being leveraged by Seabound Carbon to develop a combination onboard/onshore shipboard carbon capture system.[69] Calcium looping is a two-step cyclical process where calcium oxide (in pebble form) is loaded onto a vessel that has a Seabound carbonator installed. The shipboard exhaust gas is then routed through the carbonator where the CO_2 reacts and binds with the calcium oxide to form calcium carbonate. The calcium carbonate is then stored onboard the vessel until it reaches a port for offloading. Once the calcium carbonate is offloaded, the second part of the process occurs where the calcium carbonate is heated in a zero-emissions lime calciner to regenerate the calcium oxide and separate the CO_2. The calcium oxide can then be re-used again once loaded onto a vessel. The CO_2 can be sold or sequestered. Currently, Seabound has built a working prototype, secured backing, and garnered interest from several major shipowners. Figure 29 provides a graphical display of the Seabound calcium looping process.

[69] *Seabound Overview for Life Cycle Engineering: Ship-Based Carbon Capture Systems*. Seabound Carbon. September 2022.

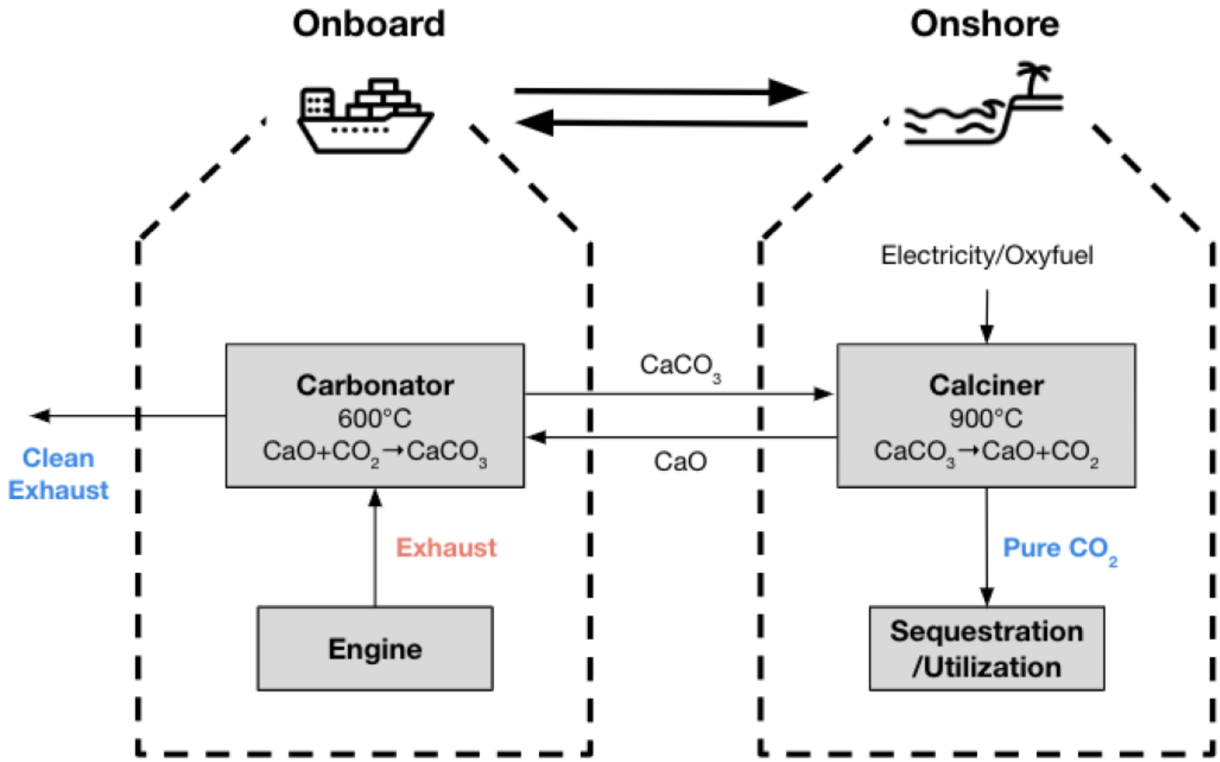

Figure 29. Seabound Carbon Onboard/Onshore Calcium Looping Process

4 Literature Review

In addition to the review of demonstration projects and technical studies summarized in Section 3, this section of the report provides a listing of the Non-Governmental Organizations (Section 4.1) that are supporting the area of shipboard carbon capture, and a short summary of the literature collected from various classification societies (Section 4.2). Appendix B provides the listing of all documents reviewed as part of this study.

4.1 Non-Government Organizations

A number of organizations have emerged to support the maritime industry in decarbonizing and reducing emissions. They have their own projects, information exchange, and are worth mentioning as they can be a good starting point and great resources in researching this carbon capture and decarbonization. These include:

- Blue Sky Maritime Coalition - Net-zero Waterborne Transportation | Blue Sky Maritime Coalition (bluesky-maritime.org)
- Environmental Defense Fund - Shipping | Environmental Defense Fund (edfeurope.org)
- Getting to Zero Coalition (Global Maritime Forum) - Getting to Zero Coalition (globalmaritimeforum.org)
- Global Center for Maritime Decarbonisation - GCMD - Global Centre for Maritime Decarbonisation | Singapore (gcformd.org)
- Green Marine - Home | Green Marine (green-marine.org)
- International Chamber of Shipping - Fuelling the Fourth Propulsion Revolution: An Opportunity for All – Full Report | International Chamber of Shipping (ics-shipping.org)
- Lloyd's Register Maritime Decarbonisation Hub - About the Lloyd's Register Maritime Decarbonisation Hub. (lr.org)
- Maersk Mc-Kinney Moller Center for Zero Carbon Shipping - Home | Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
- Ocean Conservancy - Home - Ocean Conservancy
- Oil and Gas Climate Initiative - OGCI and StenaBulk find marine carbon capture to be technically feasible
- PORTVISION50 - https://portvision50.org
- Poseidon Principles (Global Maritime Forum) - Poseidon Principles (globalmaritimeforum.org)
- Shipping Decarbonization Initiative - Aspen Shipping Decarbonization Initiative: Tackling an Urgent Challenge for #OceanClimateAction - The Aspen Institute
- Washington Maritime Blue - Washington Maritime Blue - WA Sustainable Maritime Strategy
- World Ports Sustainability Program - World Port Sustainability Program (sustainableworldports.org)
- ZESTAs. – Zero Emission Ship Technology Association - About - ZESTAs

One of the most noteworthy reports was published in May 2022 by the International Chamber of Shipping, titled "Fueling the Fourth Propulsion Revolution".[13] This document provides insight into the opportunities and challenges associated for global shipping as the maritime industry transitions itself to meet IMO GHG reduction goals. It points out that maritime decarbonization through new fuels is very dependent on the energy producers and how government and industry need to work together quickly. The most significant point made in this report is that to support the transition to new sustainable "e-fuels" will require an increase in the world's renewable energy supply by 3,000 TWh while noting that the world's current total renewable supply is nearly this amount.

4.2 Classification Societies

Several recent guidebooks and whitepapers have been published by the maritime classification societies. Lloyd's Register was noted in the previous section for their Maritime Decarbonization Hub webpage. Additionally, they have published a series of assessments and guides including "Low Carbon Pathways 2050", "Zero Emission Vessels 2030", "Zero Emission Vessels: Transition Pathways", "Techno-economic Assessment Zero Carbon Fuels", and their latest "First Movers in Shipping's Decarbonization." Most of their focus is on zero carbon fuels and renewable fuels. In their discussions, CCS plays a major role in the shoreside capture of CO_2 emissions to process zero carbon and renewable fuels using traditional energy and fuels like natural gas yielding for example, blue hydrogen. In the First Movers document, CCS is not included in the decarbonization transition; it focuses on fuel transition choice for a specific fleet and its fuel supply.

As early as 2010, Det Norske Veritas (DNV) has worked with Process Systems Enterprise on a research and development projects to develop a blueprint for on-ship carbon capture and storage.[70] In 2013, the team reported that they had successfully developed a concept design of a CCS system that included a CO_2 absorption system (amine-based) that would capture up to 65% CO_2 emissions and then liquefy it for storage.[71] Figure 30 provides a sketch of the concept design.[72] For a VLCC tanker, DNV points out that this could correspond to capturing more than 70,000 tonnes of CO_2 per year.

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[70] *DNV and PSE Joint Project for Maritime CCS*. (2010). Carbon Capture Journal. https://www.carboncapturejournal.com/news/dnv-and-pse-joint-project-for-maritime-ccs/2665.aspx.

[71] *DNV and PSE Report on Ship Carbon Capture & Storage*. (2013). The Maritime Executive. https://www.maritime-executive.com/corporate/DNV-and-PSE-Report-on-Ship-Carbon-Capture-Storage.

[72] *DNV Unveils Shipboard Carbon Capture System*. (2022). gCaptain. https://gcaptain.com/dnv-unveils-concept-design-for-shipboard-carbon-capture-system/.

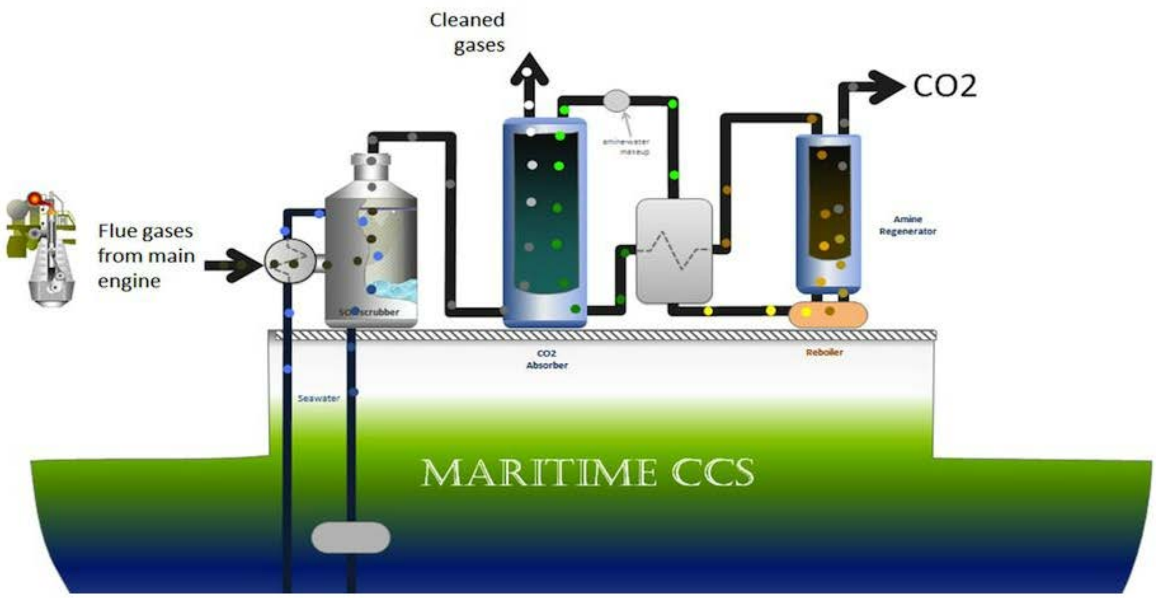

Figure 30. DNV Carbon Capture System

Det Norske Veritas has recently published a number of whitepapers and guides that discuss the ongoing energy transition outlook, including the role carbon capture and storage will take in the energy industry. APPENDIX B provides a list of the recent DNV publications related to decarbonization. In a recent webinar on April 28, 2022, DNV stated that CCS is easier to apply on LNG and LPG-fueled systems and the regulatory perspective is one of the key challenges. Additionally, the land-based infrastructure requirements are being established concurrently with other industries. They also made a point to discuss the role maritime industry will play on CO_2 transport with CO_2 carriers soon to be built.

American Bureau of Shipping (ABS) has recently published some whitepapers and guides for carbon capture and the subsequent use and/or storage as well as marine decarbonization advisory including a carbon capture discussion. The first document of note is the “Carbon Capture, Utilization, and Storage, August 2021,” which provides a good primer for the CCS space, but also adds opportunities for utilization. A top-level of the capture technologies and processes as well as the use and storage spaces. ABS published an “ABS Advisory on Decarbonization for Power Generation and Propulsion System” in 2022 that provides details on available and emerging technologies for reducing GHG emissions from a “tank-to-wake” perspective. Included in the discussion is carbon capture and provides an overview of the technologies that make up the capture space. ABS concludes that carbon capture currently faces technical and economic challenges for marine applications, but it still has potential to be an effective method of reducing GHG emissions on future vessels. They point out that this is especially true when used in conjunction with low-carbon fuels. In another recent publication, “Low Carbon Shipping Outlook” published in 2022, ABS points out that it is possible to capture CO_2 on vessels, but the challenge is the handling and storage of the CO_2 captured. It would also require significant space for storage and power to cool and liquefy the CO_2 for storage and transport.

5 Summary/Conclusions

Meeting IMO's 50% GHG reduction goals by 2050 will certainly be challenging. Meeting worldwide zero GHG emissions targets by 2050 is an even greater challenge. The recent IMO MEPC 78 meetings continue to refine the development of carbon intensity values for ships. Since IMO started down the path of reducing exhaust emissions, including CO_2, the actions taken using EEDI and SEEMP activities have already reduced the carbon intensity of ships by 32% (compared to 2008).[73] This is a significant achievement. However, it is not enough and other solutions will be required to achieve these goals. The solution is complicated and no single solution will fit all vessels. All options, including carbon capture, must be considered as operators move to meet the IMO goals.

Prior to the IMO 2050 GHG reduction goals, there was already momentum to reduce maritime exhaust emissions. Implementation of EPA Tier levels for improvement of diesel engine exhaust emissions including NOx, particulate matter, and CO; development of EEDI and SEEMP by IMO; implementation of EPA Cat 2 engine rules for burning 15 ppm max sulfur fuels; and ECA area implementation have all improved the maritime operational and exhaust emission landscape. The latter, for example, caused operators who trade in the ECA areas to make a decision between switching to a lower sulfur fuel or scrubbing the sulfur from exhaust gases. Regulators considered either method acceptable and both were installed by ship owners to meet the requirements. Fuel switching required modifications to bunker and fuel systems, engine modifications, and operational changes while sulfur scrubbing required installation of equipment in the exhaust stack as well as a scrubber water treatment unit. Both of these solutions also required modifications to the traditional shoreside logistics processes to accommodate different fuels as well as the process fluids and sulfur from the scrubbers. Some operators even chose to make a dramatic switch in fuel to natural gas, which is a cleaner fuel in terms of criteria pollutants but can be a wash for CO_2, due to methane slip.

The paradigm has now shifted. Now, all hydrocarbon fuels including natural gas (unless produced from renewable sources) and biofuels (unless synthetically derived using renewable energy sources) are likely to be phased out. For example, companies like MAN are developing synthetic natural gas production facilities that use hydrogen produced by electrolysis and captured CO_2 to produce methane using renewable energy sources.[74] This is happening worldwide in every industry – replacing hydrocarbon fuels is a top priority for GHG reduction – unless there is an efficient method to capture carbon in exhaust. The U.S. DOE is providing $3.5B dollars in funding for projects to demonstrate carbon capture for direct air capture and for point sources like cement plants, ammonia production plants, and power plants.[7] This carbon capture research activity is good news for mobile sources, such as ships, because

[73] Comer, B. (2021). *Choose Wisely: IMO's Carbon Intensity Target Could be The Difference Between Rising or Falling Shipping Emissions this Decade*. The International Council on Clean Transportation. https://theicct.org/choose-wisely-imos-carbon-intensity-target-could-be-the-difference-between-rising-or-falling-shipping-emissions-this-decade/

[74] *SNG - Synthetic Natural Gas*. (2022). MAN Energy Solutions. https://www.man-es.com/discover/decarbonization-glossary---man-energy-solutions/synthetic-natural-gas.

improvements and cost reductions in the technology will make it more attractive as a potential option for the maritime industry. This research will also likely benefit the industry since CO_2 will likely need to be shipped as a commodity around the globe.

The IEA has projected that to meet the renewable energy requirements to fulfill all of the power requirements for a decarbonized future, an additional 36,770 TWh needs to be added to the current global demand of 23,230 TWh.[13] In 2021, the IEA reported that renewable electricity reached 8,300 TWh.[75] While this is a step in the right direction, the world has its work cut out for it to achieve 60,000 TWh of renewable energy by 2050. The International Chamber of Shipping estimated that to provide the energy for fuels to decarbonize worldwide shipping will require approximately 3,000 TWh of renewable electricity.[13] Production of clean fuels like zero-carbon fuels (hydrogen and ammonia) and synthetically-derived e-fuels (methanol, natural gas, biofuels) will ramp up to use renewable energy as it develops, but in the meantime can use traditional energy sources, especially if carbon capture is deployed at the power source. Significant infrastructure improvements to handle the zero-carbon fuels will also need to be developed along with fuel production.

It is clear that the maritime industry must continue to evolve their strategy to meet IMO 2050 50% GHG reduction goals as well as the current US Administration's quest for zero GHG emissions by 2050.[2,5] At this point, no technology, including carbon capture, should be eliminated from consideration. This is especially true, given that the maritime industry only accounts for approximately 3% of the world's GHG emissions, and the other 97% of emitters are also working toward a similar path to reach zero GHG emissions. Some other industries have even fewer options than the maritime industry. For example, the aircraft industry is similar to the maritime industry in that it also contributes nearly 3% of global GHG emissions, but they have fewer options since net-zero fuels like hydrogen or e-methanol, as well as synthetic natural gas, will not work well in aircraft. Therefore, the aviation industry is focused more heavily in the development of sustainable aviation fuels produced by renewable power sources.[76] Fortunately, the maritime industry has more options available for consideration.

Recently, several maritime industry leaders, including ABS, concluded that shipboard carbon capture and storage must play a role in the net-zero GHG transformation.[14] Based on a review of the technologies available, we agree and conclude that CCS is an option that needs to be considered. What makes CCS particularly attractive as a solution is that it does not require any changes to the current fueling infrastructure, it does not compete with other sectors working towards the same goal, and it benefits greatly from the increased amount of carbon capture technology development research that is ongoing worldwide for point sources.

Most of the studies and demonstrations reviewed have used chemical absorption technology as the capture system of choice since it is the most technically mature and commercially available. A couple of studies also discussed cryogenic capture as an alternative; however, this technology is still not mature

[75] *Renewables – Global Energy Review 2021 – Analysis*. (2021). IEA. https://www.iea.org/reports/global-energy-review-2021/renewables.
[76] *Aviation's Flight Path to a Net-Zero Future*. (2022). World Economic Forum. https://www.weforum.org/agenda/2021/09/aviation-flight-path-to-net-zero-future/.

enough for marine use and requires the most additional power. Membrane separation system requirements for a higher CO_2 concentration in the exhaust stream, combined with lower capture rate, make this poorly suited as a shipboard option. Finally, physical separation (adsorption) technology appears to be a good option for marine use. It has a capture rate similar to chemical absorption systems, does not require any toxic chemicals, and is more scalable to marine propulsion and generator equipment. While physical separation carbon capture systems have not been demonstrated at large scale, sorbent systems are commercially available in large scale for applications such as dehydration, hydrogen separation, nitrogen generation, oxygen generation, etc., so the lessons learned from these applications can be leveraged to develop this technology for large-scale carbon capture.

As with insertion of any new technology on marine vessels, carbon capture and storage integration is not without challenges. Some of the challenges are similar to other marine greenhouse gas reduction solutions proposed, such as net-zero carbon fuels or zero carbon fuels, while some are unique to carbon capture and storage technology. Table 13 provides a list of some of the challenges associated with CCS technology and the opportunity to resolve them through continued technology development and demonstrations.

Table 13. CCS Challenges and Opportunities

Challenge	CCS Problem	Opportunity
Technology Maturity	The maturity of each capture method ranges from high for chemical absorption, medium for membrane separation and physical separation, and low for cryogenic separation and oxy-fuel separation.	U.S. DOE is funding a significant amount of research and demonstration for point sources. This should move physical separation and membrane separation technologies forward. EU is looking at cryogenic as well.
CAPEX	High CAPEX is the problem cited by every study since carbon capture, packaging, and storage require equipment and investment. Some solutions may require additional auxiliary generators to meet power requirements.	A combination of research, equipment production, and design optimization is needed to minimize the amount of storage tanks required, as tanks are the significant cost driver.
OPEX	Increased power/fuel, maintenance, labor, and replacement of working fluids all add to ship operating expenses.	Matching CCS technology with ship type and operation. LNG ships, for example, require less energy since vaporization of natural gas helps liquefy CO_2. Other design optimization can be made with more demonstration project results.
CO_2 Storage	CO_2 storage options include pressurized gas or liquid storage. High purity CO_2 is also a requirement for storage to ensure it can be compatible with shoreside use or sequestration.	This study, and all others that were reviewed, conclude that liquid CO_2 storage is the most efficient way to store CO_2 on a vessel.

Challenge	CCS Problem	Opportunity
Marinization	Most carbon capture equipment is designed for point source applications that do not have space or weight restrictions whereas vessels have space/weight issues. Additionally, the equipment has not been designed for use in the marine environment.	Demonstration projects will help progress marine design needs as well as rules/design guideline development from classification and regulatory groups for marine equipment and CO_2 handling.
Volume/Weight Penalty	Twofold issue – 1) weight and volume of equipment added and 2) CO_2 captured for storage is heavier than fuel consumed. These can create stability issues and impact cargo carrying ability.	Research and design improvements along with selecting the right capture technology will improve CCS footprint. Optimizing trip planning to "right size" storage tanks is required to reduce impact.
Exhaust System Design	Traditional marine exhaust design routes engine exhausts from engines up through exhaust stacks to the atmosphere. Likely carbon capture system design will be units designed for full engine exhaust capture.	Exhaust manifold designs will be required to interconnect engine exhausts to prevent backflow and cause minimal backpressure influences.
Engine Loading	Point source capture technologies are usually sized for plant operation whereas mobile sources like ships have their engines operate at both transient loads (maneuvering) and part load.	Carbon capture system technology needs to be evaluated on a ship-by-ship case to ensure proper sizing and turndown is available.
Capture Rate/Purity	Two drivers for CCS system design are capture rate and purity. Both are functions of the capture system method and impact storage and packaging equipment requirements.	Selection of the right capture technology to use in addition to performing tradeoff analyses are essential to consider the economics of the capture rate. For example, the extra energy required to achieve a capture rate of 95% in an absorption system may require more power/fuel when a 50% capture rate may be more optimal.
CO_2 Infrastructure	CCS needs to rely on the ability to offload CO_2 in port. Shoreside infrastructure for movement of CO_2, especially in ports, is relatively nonexistent.	As the maritime industry develops CO_2 carriers to move it as cargo to various CCUS hubs worldwide, the infrastructure and transport equipment will be developed.

We conclude that CCS is technically feasible for shipboard application based on the technical studies, demonstrations, and literature reviewed. Whether it is economically feasible or operationally practical remains to be seen. While CCS cannot reduce carbon emissions to zero, it has potential to provide a significant reduction in carbon emissions until such time that zero carbon fuels and the associated infrastructure can be put into place. Implementation of shipboard CCS should be considered in three parts:

- Add CCS to existing shipboard SOx scrubbers

  This is the nearest-term solution since it uses existing scrubber technology but would still require investment for purification and storage of the captured CO_2. This has the potential to quickly provide a modest reduction in carbon emission.

- Add CCS to select vessels

  Carbon capture won't likely work on all vessels, either due to the size/weight/power requirements or simply due to the vessels' routes and ability to offload captured CO_2. Implementation of carbon capture on vessels where the size/weight/power requirements can be accommodated and the vessel has the means to offload captured CO_2 is a near-term solution that can provide a significant reduction in carbon emissions

- Add CCS onboard bulk CO_2 carriers

  Carbon capture onboard bulk CO_2 carriers would provide the ultimate near-term solution, since the carriers already have the CO_2 tankage onboard. The only investment required would be for the capture and purification of the CO_2.

As shown in Table 13, there are many challenges to CCS integration, but the same can be said for just about any of the other alternatives except drop-in replacement bio-derived fuels. While CCS does not provide a 100% reduction in carbon emissions, it does offer a short-term solution to make an immediate impact on a vessel's carbon emissions and will likely help many operators meet IMO 2050's 50% GHG reduction target. It will definitely reduce the carbon intensity of every vessel, but is likely only suited to certain vessel types or operations. Further, marine demonstration and capture technology development is required to reduce the size, improve the efficiency, and reduce power requirements.

The LCE team recommends the following future work:

- Host a seminar to discuss the shipboard carbon capture space – DOE/MARAD Joint Seminar planning is underway and expected to be held by the end of August 2022.
- Further techno-economic study – 2nd phase of this project will evaluate both an ocean-going and inland waterway vessel on available data and vendor capture data.
- Create carbon capture database of vendors, projects, and operators.
- Demonstrate CCS System on a vessel – recommend either a harbor vessel or inland waterways towboat.

APPENDIX A: Storage Calculations

APPENDIX A-1: Calculation of Carbon Dioxide Emissions

Diesel engine carbon dioxide emissions from conventional hydrocarbon fuels is calculated as follows:[77]

Known:

#1 diesel fuel average molecular weight is 170

#2 diesel fuel average molecular weight is 184

Heavy diesel fuel molecular average weight is 198

Calculated:

#1 Diesel

Hydrocarbon C12H26 has a molecular weight of 170

The combustion equation is:

C12H26 + 18.5O2 = 12CO2 + 13H2O

The molecular weight of 12CO2 is 12(12+2*16) = 12*44 = 528

Therefore, the production of carbon dioxide by weight is 528/170 = 3.10 times the original hydrocarbon weight.

#2 Diesel

Hydrocarbon C13H28 has a molecular weight of 184

The combustion equation is:

C13H28 + 20O2 = 13CO2 + 14H2O

The molecular weight of 13CO2 is 13(12+2*16) = 13*44 = 572

Therefore, the production of carbon dioxide by weight is 572/184 = 3.11 times the original hydrocarbon weight.

Heavy Fuel

Hydrocarbon C14H30 has a molecular weight of 198

The combustion equation is:

C14H30 + 22.5O2 = 14CO2 + 15H2O

The molecular weight of 14CO2 is 14(12+2*16) = 14*44 = 616

[77] Culp, A. W. (1979). *Principles of Energy Conversion*. McGraw-Hill.

Therefore, the production of carbon dioxide by weight is 616/198 = 3.11 times the original hydrocarbon weight.

Conclusion:

For each pound of fuel burned in a diesel engine, approximately 3.1 pounds of carbon dioxide is produced. This approximation holds true for any of the conventional hydrocarbon fuels commonly used in diesel engines.

APPENDIX A-2: Fuel Consumption Calculation

Estimated diesel engine fuel consumption for selected scenarios are calculated as follows:

Scenarios:

The first scenario is a harbor tug that can readily offload captured CO_2. This vessel is assumed to have a total of 1000 horsepower (hp). The vessel's engines operate on average at 50% maximum continuous rating (MCR) for a 12-hour day. The vessel will offload stored CO_2 once a week.

The second scenario is a large river towboat in the river trade. This vessel is assumed to have a total of 4,000 hp, and have engines operating at an average of 80% MCR for a 24 hour day. The vessel will offload captured CO_2 every two weeks.

The third scenario is a large ocean-going vessel in international trade. This vessel is assumed to have a total of 20,000 hp, and have engines operating at an average of 80% MCR for a 24 hour day. The vessel will offload captured CO_2 every four weeks.

Assumed:

The harbor tug (1st scenario) is powered with two Cummins QSK19 IMO III main engines. Each engine has a continuous rating of 500 hp, and a fuel consumption of 26.5 gallons per hour.78

The large river towboat (2nd scenario) is powered with two Cummins QSK60 main engines. Each engine has a continuous rating of 2,000 hp, and a fuel consumption of 95.4 gallons per hour.78

The large ocean-going vessel (3rd scenario) is powered with one slow speed Mitsubishi 5 cylinder UEC75LSII main engine. The main engine has a continuous rating of 20,000 hp, and a fuel consumption of 121 grams per horsepower hour.[79]

An additional assumption is that the fuel consumption decreases in proportion to engine output at partial power. This assumption should not cause an error greater than about 10%.

Calculated Fuel Consumption:

Scenario 1 (harbor towboat) – For seven 12-hour days at 50% MCR

12 hours per day * 7 days = 84 running hours

84 hours * 26.5 gallons/hour * 2 engines* 0.5 (50% MCR) = 2226 gallons

2226 gallons (7.1 lb/gal (#2 diesel fuel)[77]) = 15,805 lbs of fuel

Scenario 2 (large river towboat) – For 14 days at 80% of MCR

[78] Cummins. (2022). *Cummins Marine Products Guide*. https://mart.cummins.com/imagelibrary/data/assetfiles/0032264.pdf.

[79] Mitsubishi. (n.d.). *Mitsubishi Diesel Engine Catalog*. https://engine.od.ua/ufiles/Mitsubishi_UE_diesel_catalogue.pdf.

24 hours/day * 14 days = 336 hours

336 hours * 95.4 gallons/hour * 2 engines* 0.8 (80% MCR) = 51,290 gallons

51,290 gallons (7.1 lb/gal (#2 diesel fuel)[77]) = 364,160 lbs of fuel

Scenario 3 (large ocean-going vessel) – For 28 days at 80% of MCR

24 hours/day * 28 days = 672 hours

672 hours * 20,000 hp * 121 grams/horsepower-hour * 1 engine* 0.8 (80% MCR) = 1,300,992,000 grams

1,300,992,000 grams * (1lb/454 gm) = 2,865,620 lbs of fuel

APPENDIX A-3: Storage Tank Calculation

Section 3 of this report's main body describes the three candidate storage options (gaseous, liquid, and supercritical fluid). Section 4 of this report's main body describes the three operating scenarios. Required storage tank sizes are calculated for each operating scenario and each storage condition.

Scenario 1 – Harbor Towboat

In scenario 1, storage for 48,995 pounds of CO_2 is required.

The density of CO_2 stored as a refrigerated liquid is 67.0 lb/ft3. The storage volume required is 48,995/67.0 = 732 ft3

The density of CO_2 stored as a high pressure (3000 psi) fluid is 51.7 lb/ft3. The storage volume required is 48,995/51.7 = 948 ft3

The density of CO_2 stored as a compressed gas at 800 psia is 7.91 lb/ft3. The storage volume required is 48,995/7.91 = 6194 ft3

Scenario 2 – Large River Towboat

In scenario 2, storage for 364,160 pounds of CO_2 is required.

The density of CO_2 stored as a refrigerated liquid is 67.0 lb/ft3. The storage volume required is 364,160/67.0 = 5435 ft3

The density of CO_2 stored as a high pressure fluid is 51.7 lb/ft3. The storage volume required is 364,160/51.7 = 7045 ft3

The density of CO_2 stored as a compressed gas at 800 psia is 7.91 lb/ft3. The storage volume required is 364,160/7.91 = 46,040 ft3

Scenario 3 – Ocean-going Vessel

In scenario 3, storage for 8,883,420 pounds of CO_2 is required.

The density of CO_2 stored as a refrigerated liquid is 67.0 lb/ft3. The storage volume required is 8,883,420/67.0 = 132,590 ft3

The density of CO_2 stored as a high pressure fluid is 51.7 lb/ft3. The storage volume required is 8,883,420/51.7 = 171,825 ft3

The density of CO_2 stored as a compressed gas at 800 psia is 7.91 lb/ft3. The storage volume required is 8,883,420/7.91 = 1,123,065 ft3

Refrigerated Liquid Storage

A candidate storage system is by Chart Industries. Each package is rated to 350 psi, and stores CO_2 at about -20^{o}F. The storage volume of each package is 978 ft^{3}. Each cylinder package is approximately 329 inches long, 114 inches wide, 140 inches high, and weighs 45,400 pounds empty. The HS-30 tank actual capacity is 19,370 pound of CO_2 per tank, since it is not completely filled with liquid CO_2. For the harbor towboat, 48,995 lbs/19370 lbs = 2.53, (use 3) storage packages are required. The tank and CO_2 weight is

48,995 + 3* 45,400 = 185,95 pounds (82.7 long tons). The deck area required for the tank is about 3*329*114/144 = 780 square feet. Note that the CO_2 storage tank is just under 12 feet high.

For the large river towboat,, 1,128,900 lbs/19370 lbs = 58.3, (use 59) storage packages are required. The tank and CO_2 weight is 1,128,900 + 59 * 45,400 = 3,807,500 pounds (1700 long tons). The deck area required for the tank is about 59*329*114/144 = 15,340 square feet.

For the ocean-going vessel, 8,883,420 lbs/19370 lbs = 458.6, (use 459) storage packages are required. The tank and CO_2 weight is 8,883,420 + 459 * 45,400 = 27,922,020 pounds (13,268 long tons). The deck area required for the tank is about 459*329*114/144 = 119,340 square feet.

Fluid Storage:

A candidate storage system is by Texas Trailer.80 Each cylinder package is rated to 3600 psi. This provides some margin if used at 3,000 psi. The storage volume of each cylinder package is 356 ft3. Each cylinder package is approximately 34 feet 5 inches long, 101 inches wide, 47 inches high, and weighs 47,600 pounds empty. For the harbor towboat, 948 ft3/356 ft3 = 2.67, (use 3) cylinder packages are required. The tank and CO_2 weight is 48,995 + 3* 47,600 = 191,795 pounds (85.6 long tons). A two high stack will require approximately 36 ft*8.5 ft*2 tank stacks = 612 square feet.

For the large river towboat, 7045 ft3/356 ft3 = 19.8, (use 20) cylinder packages are required. The tank and CO_2 weight is 364,160 + 20* 47,600 = 1,316,160 pounds (587.6 long tons). A two high stack will require approximately 36 ft*8.5 ft*10 tank stacks = 3060 square feet.

For the ocean-going vessel, 171,825 ft3/356 ft3 = 482.7, (use 484) cylinder packages are required. The tank and CO_2 weight is 8,883,420 + 484* 47,600 = 31,921,820 pounds (14,251 long tons). A two high stack will require approximately 36 ft*8.5 ft*242 tank stacks = 74,052 square feet.

Compressed Gas Storage:

Compressed gas storage requires pressure vessels similar to high-pressure fluid storage. Each 800 psi pressure vessel will be somewhat lighter than the pressure vessels used for 3000 psi supercritical fluid storage. The pressure vessel volume requirement for compressed gas storage is about 6.5 times the high-pressure fluid storage. Using calculations similar to the supercritical calculation, or the harbor towboat, 6194 ft3/356 ft3 = 17.4, (use 18) cylinder packages are required. The tank and CO_2 weight is 48,995 + 18* 47,600 = 905,795 pounds (404.4 long tons). A two high stack will require approximately 36 ft*8.5 ft*9 tank stacks = 2754 square feet. For the large river towboat, 46,040 ft3/356 ft3 = 129.3, (use 130) cylinder packages are required. The tank and CO_2 weight is 364,160 + 130* 47,600 = 6,552,160 pounds (2925 long tons). A two high stack will require approximately 36 ft *8.5 ft *65 tank stacks = 19,890 square feet.

[80] Texas Trailer Corporation. (n.d.). *8 Tube Storage Pack, Drawing No. 75000-AB*.

For the ocean-going vessel, 1,123,065 ft3/356 ft3 = 3154.6, (use 3155) cylinder packages are required. The tank and CO_2 weight is 8,883,420 + 3155 * 47,600 = 159,061,420 pounds (71,009 long tons). A two high stack will require approximately 36 ft * 8.5 ft * 1578 tank stacks = 482,868 square feet.

The equipment size calculated for compressed gas storage is so high, that compressed gas storage is clearly impractical.

APPENDIX A-4: Estimated Energy Requirements

For the harbor boat, the auxiliaries have to be sized for full power, even though the normal CO_2 production is based on 50% power. The fuel consumption is 2*26.6 gal/hr = 53.2 gal/hr. The CO_2 production is 53.2 gal/hr*7.5 lb/gal* 3.1 lb CO_2/lbfuel = 1232 lb CO_2/hr.

For the large river boat, the auxiliaries also have to be sized for full power even though the normal CO_2 production is based on 80% power. The fuel consumption is 2*95.4 gal/hr = 190.8 gal/hr. The CO_2 production is 190.8 gal/hr*7.5 lb/gal* 3.1 CO_2/lbfuel = 4436 lb CO_2/hr.

For the large ocean-going vessel, the auxiliaries also have to be sized for full power. The fuel consumption is 20000 hp * 121 gm/hp-hr *1/454 gm/lb = 5330 lb/hr. The CO_2 production is 5330 lb/hr* 3.1 CO_2/lbfuel = 16,525 lb CO_2/hr.

To compress the CO_2 from atmospheric pressure to 300 psi, the harbor boat will require a compressor of approximately 75 horsepower (55 kW).[81]

For the large river boat, the compressor required to compress the CO_2 from atmospheric pressure to 300 psi will require a compressor of approximately 270 horsepower (200 kW).[81]

For the large ocean-going vessel, the three compressors required to compress the CO_2 from atmospheric pressure to 300 psi will require compressors totaling approximately 800 horsepower (600 kW).[81]

Most of the dehydration will be done during the CO_2 compression. There will be some additional dehydration required, but that can largely be done with the refrigeration equipment or dessicant driers that will not require large amounts of power (the amount of drying required is not large).

The energy removal required to cool and liquefy compressed CO_2 from approximately 100°F to -20°F is the difference in enthalpy between the two conditions, or approximately 214.6 BTU/lb – 58.4 BTU/lb = 156.2 BTU/lb. Each ton of refrigeration can reduce the temperature of about 77 pounds of compressed CO_2 from 100°F to -20°F. For the harbor towboat, the refrigeration cooling capacity required is 1232 lb CO_2/hr / 77 lb/ton = 16 tons of refrigeration. For the large river boat, the refrigeration cooling capacity required is 4436 lb CO_2/hr / 77 lb/ton = 58 tons of refrigeration. For the large ocean-going vessel, the refrigeration cooling capacity required is 16,525 lb CO_2/hr / 77 lb/ton = 215 tons of refrigeration.

The power required per ton of refrigeration is approximately 2.2 kW per ton of refrigeration.[82] For the harbor boat, the kW required is 16 tons * 2.2 kW/ton = 35 kW. For the large river towboat, the kW required is 58 tons * 2.2 kW/ton = 128 kW. For the large ocean-going vessel, the kW required is 215 tons * 2.2 kW/ton = 475 kW.

Each liquid CO_2 storage tank requires cooling to maintain -20°F. The surface area of each liquid storage tank is approximately 820 ft^2.[40] The cooling required is approximately (0.04 BTU/hr-ft^2-°F)(100°F - (-

[81] Atlas Copco. (n.d.). *Oil-Free Process Gas Compressors*. https://www.atlascopco.com/content/dam/atlas-copco/compressor-technique/oil-free-air/documents/CO2%20booster%20Leaflet%20EN%20.pdf.
[82] Carrier. (2001). *Sea Horse 90Y Condensing Unit*. https://www.carrier.com/marine-offshore/en/worldwide/products/condensing-units/90y/.

20^{o}F))(820 ft^2) = 3936 BTU/hr, or 0.33 tons. For each tank, the refrigeration system will require an electrical input of about 0.75 kW.

APPENDIX A-5: Regulatory Requirements and Information

A-5.1: U.S Code of Federal Regulations Excerpts

The U.S. Code of Federal Regulations has the following requirements that apply to vessels carrying carbon dioxide:

54.03-1 Scope.

The pressure vessels for low temperature operation shall be as required by section VIII of the ASME Boiler and Pressure Vessel Code (incorporated by reference; see 46 CFR 54.01-1) as modified by this subpart.

154.170 Outer hull steel plating.

(a) Except as required in paragraph (b) of this section, the outer hull steel plating, including the shell and deck plating must meet the material standards of the American Bureau of Shipping published in "Rules for Building and Classing Steel Vessels" 1981.

(b) Along the length of the cargo area, grades of steel must be as follows:

> (1) The deck stringer and sheer strake must be at least Grade E steel or a grade of steel that has equivalent chemical properties, mechanical properties, and heat treatment, and that is specially approved by the Commandant (CG-ENG).
>
> (2) The strake at the turn of the bilge must be Grade D, Grade E, or a grade of steel that has equivalent chemical properties, mechanical properties, and heat treatment, and that is specially approved by the Commandant (CG-ENG).
>
> (3) The outer hull steel of vessels must meet the standards in § 154.172 if the hull steel temperature is calculated to be below −5 °C (23 °F) assuming:
>
> > (i) For any waters in the world, the ambient cold conditions of still air at 5 °C (41 °F) and still sea water at 0 °C (32 °F);
> >
> > (ii) For cargo containment systems with secondary barriers, the temperature of the secondary barrier is the design temperature; and
> >
> > (iii) For cargo containment systems without secondary barriers, the temperature of the cargo tank is the design temperature.

CFR 154.170 requires that the secondary barrier material has to be rated for the liquid or gas storage temperature.

56.01-10 Plan Approval.

(a) Plans and specifications for new construction and major alterations showing the respective piping systems shall be submitted, as required by subpart 50.20 of this subchapter.

(b) Piping materials and appliances, such as pipe, tubing, fittings, flanges, and valves, except safety valves and safety relief valves covered in part 162 of subchapter Q (Specifications) of this chapter, are not required to be specifically approved by the Commandant, but shall comply with the applicable requirements for materials, construction, markings, and testing. These materials and appliances shall be certified as described in part 50 of this subchapter. Drawings listing material specifications and showing details of welded joints for pressure-containing appurtenances of welded construction shall be submitted in accordance with paragraph (a) of this section.

(c)

(1) Prior to installation aboard ship, diagrams of the following systems shall be submitted for approval:

(i) Steam and exhaust piping.

(ii) Boiler feed and blowoff piping.

(iii) Safety valve escape piping.

(iv) Fuel oil service, transfer and filling piping. (Service includes boiler fuel and internal combustion engine fuel piping.)

(v) Fire extinguishing systems including fire main and sprinkler piping, inert gas and foam.

(vi) Bilge and ballast piping.

(vii) Tank cleaning piping.

(viii) Condenser circulating water piping.

(ix) Vent, sound and overflow piping.

(x) Sanitary drains, soil drains, deck drains, and overboard discharge piping.

(xi) Internal combustion engine exhaust piping. (Refer to part 58 of this subchapter for requirements.)

(xii) Cargo piping

(xvii) Refrigeration and air conditioning piping

(2) Arrangement drawings of the following systems shall also be submitted prior to installation:

(i) All Classes I, I-L, and II-L systems.

56.50-105 Low-temperature piping.

(a) Class I-L. Piping systems designated to operate at temperatures below 0 °F and pressures above 150 pounds per square inch gage shall be of Class I-L. Exceptions to this rule may be found in the individual requirements for specific commodities in subchapters D, I, and O of this chapter.

The ABS Rules for Building and Classing Marine Vessels (July 2020) Part IV chapter 7 section 3.5 covers refrigerated CO_2 storage for firefighting systems. These ABS requirements should generally cover refrigerated CO_2 storage for shore disposal. The ABS rules state:

Refrigerated Low-pressure CO_2 Systems

The use of refrigerated CO_2 as a fire-extinguishing medium, at a pressure of 18 to 22 bar (260 to 320 lb/in2) in the storage condition, is to be in accordance with 4-7-3/3.1 and 4-7-3/3.3 and the following additional requirements.

3.5.1 Plans and Data to be Submitted

The system control devices and the refrigerating plants are to be located within the same room where the pressure containers are stored.

- System schematic arrangement
- CO_2 capacity and flow calculations
- System control and alarm arrangement
- Arrangement of CO_2 containers and refrigerating plant
- Construction details of CO_2 containers
- Manufacturer's specifications for compressor, condenser, receiver, evaporator, etc.
- Piping diagram for refrigerating system
- Electrical wiring diagrams

3.5.2 CO_2 Containers

3.5.2 (a) Capacity.

The rated amount of liquid carbon dioxide is to be stored in container(s) under the working pressure in the range of 18 to 22 bar (260 to 320 lb/in2). The normal liquid charge in the container is to be limited to provide sufficient vapor space to allow for expansion of the liquid under the maximum storage temperatures that can be obtained corresponding to the setting of the pressure relief valves but is not to exceed 95% of the volumetric capacity of the container.

3.5.2 (b) Design and construction

CO_2 containers are to be designed, constructed, and tested in accordance with the requirements of Section 4-4-1; see in particular 4-4-1/1.11.4.

3.5.2 (c) Instrumentation and alarms

Each container is to be fitted with the following instruments and alarms at the storage location:

- Pressure gauge
- High pressure alarm set at not more than the relief valve setting
- Low pressure alarm set at not less than 18 bar (260 lb/in2)
- Level indicator fitted on the container(s)
- Any one of the refrigerating units fails to operate
- The lowest permissible level of the liquid in the container(s) is reached

A summary alarm for any of these alarm conditions is also to be given in the manned propulsion machinery space or the centralized control station (see 4-9-5/7 and 4-9-6/9), as appropriate. In the engineers' accommodation area (see 4-9-6/19).

3.5.2 (d) Relief valves

The two safety relief valves are to be arranged so that either valve can be shut off while the other is connected to the container. The setting of the relief valves is not to be less than 1.1 times the working pressure. The capacity of each valve is to be such that the vapours generated under fire conditions can be discharged with a pressure rise not more than 20% above the setting pressure. The discharge from the safety valves is to be led to the open air.

3.5.2 (e) Insulation

The container(s) and outgoing pipes permanently filled with carbon dioxide are to have thermal insulation preventing the operation of the safety valve in 24 h after de-energizing the plant, at ambient temperature of 45°C (113°F) and an initial pressure equal to the starting pressure of the refrigeration unit. Where porous or fibrous insulation materials are used, they are to be protected by impervious sheaths from deterioration by moisture.

3.5.2 (f) Main Shutoff Valve

The container main shutoff valve is to be kept locked open (LO) at all times. The valve is to be provided with a means to indicate whether the valve is open or closed. The indicator is to rely on movement of the valve spindle.

3.5.3 Refrigerating Plant

3.5.3 (a) Duplication of plant

The container(s) is(are) to be serviced by two automated completely independent refrigerating units solely intended for this purpose, each comprising a compressor and the relevant prime mover, evaporator and condenser. Provision is to be made for local manual control of the refrigerating plant. Upon failure or stoppage of the unit in operation, the other unit is to be put into operation automatically. This change-over is to be alarmed at the manned propulsion machinery space or the centralized control station, as appropriate; and, in the case of unattended propulsion machinery space, at the engineers' accommodation. See also 4-7-3/3.5.2(c). Each electric refrigerating unit is to be supplied from the main switchboard busbars by a separate feeder.

3.5.3 (b) Performance criteria

The refrigerating capacity and the automatic control of each unit are to be so as to maintain the required temperature under conditions of continuous operation during 24 h at sea temperatures up to 32°C (90°F) and ambient air temperatures up to 45°C (113°F). See also insulation requirement in 4-7-3/3.5.2(e).

3.5.3 (c) Cooling water supply

Cooling water supply to the refrigerating plant (where required) is to be provided from at least two circulating pumps one of which being used as a stand-by. The stand-by pump may be a pump used for other services so long as its use for cooling would not interfere with any other essential service of the vessel. Cooling water is to be taken from not less than two sea connections, preferably one port and one starboard.

3.5.4 Piping

3.5.4 (a) General. Pipes, fittings, and pipe joints are to be designed, fabricated and tested, and to be of materials according to the piping classes to be determined in accordance with in 4-6-1/5. Branch pipes with stop valves for filling the container are to be provided.

3.5.4 (b) CO_2 distribution piping. CO_2 flow from storage containers to the discharge nozzle is to be in liquid phase. The design pressure at the nozzle is not to be less than 10 bar (145 lb/in2).

3.5.4 (c) Safety relief valve. Safety relief devices are to be provided in each section of pipe that may be isolated by block valves and in which there could be a buildup of pressure in excess of the design pressure of any of the components. See 4-6-2/9.9.3 and 4-7-3/3.1.2 for safety valves discharge arrangement.

A-5.2: ABS Marine Vessel Rules Excerpts

The ABS Rules for Building and Classing Marine Vessels (July 2020) Part 5C chapter 8 section 17, subsections 21 and 22 covers refrigerated CO_2 storage. This section covers "Vessels Intended to Carry Liquefied Gases in Bulk". Although the carbon dioxide storage for this study's vessel may not qualify the vessel as a bulk liquefied carrying vessel, the requirements of this section still should be met. The requirements of this subsection are:

21 Carbon dioxide: high purity

21.1

Uncontrolled pressure loss from the cargo can cause "sublimation" and the cargo will change from the liquid to the solid state. The precise "triple point" temperature of a particular carbon dioxide cargo shall be supplied before loading the cargo, and will depend on the purity of that cargo, and this shall be taken into account when cargo instrumentation is adjusted. The set pressure for the alarms and automatic actions described in this section shall be set to at least 0.05 MPa above the triple point for the specific cargo being carried. The "triple point" for pure carbon dioxide occurs at 0.5 MPa gauge and –54.4°C.

21.2

There is a potential for the cargo to solidify in the event that a cargo tank relief valve, fitted in accordance with 5C-8-8/2, fails in the open position. To avoid this, a means of isolating the cargo tank safety valves shall be provided and the requirements of 5C-8-8/2.9.2 do not apply when carrying this carbon dioxide. Discharge piping from safety relief valves shall be designed so they remain free from obstructions that could cause clogging. Protective screens shall not be fitted to the outlets of relief valve discharge piping, so the requirements of 5C-8-8/2.15 do not apply.

21.3

Discharge piping from safety relief valves are not required to comply with 5C-8-8/2.10, but shall be designed so they remain free from obstructions that could cause clogging. Protective screens shall not be fitted to the outlets of relief valve discharge piping, so the requirements of 5C-8-8/2.15 do not apply.

21.4

Cargo tanks shall be continuously monitored for low pressure when a carbon dioxide cargo is carried. An audible and visual alarm shall be given at the cargo control position and on the bridge. If the cargo tank pressure continues to fall to within 0.05 MPa of the "triple point" for the particular cargo, the monitoring system shall automatically close all cargo manifold liquid and vapour valves and stop all cargo compressors and cargo pumps. The emergency shutdown system required by 5C-8-18/10 may be used for this purpose.

21.5

All materials used in cargo tanks and cargo piping system shall be suitable for the lowest temperature that may occur in service, which is defined as the saturation temperature of the carbon dioxide cargo at the set pressure of the automatic safety system described in 5C-8-17/21.1.

21.6

Cargo hold spaces, cargo compressor rooms and other enclosed spaces where carbon dioxide could accumulate shall be fitted with continuous monitoring for carbon dioxide build-up. This fixed gas detection system replaces the requirements of 5C-8-13/6, and hold spaces shall be monitored permanently even if the ship has type C cargo containment.

22 Carbon dioxide: reclaimed quality

22.1

The requirements of 5C-8-17/21 also apply to this cargo. In addition, the materials of construction used in the cargo system shall also take account of the possibility of corrosion, in case the reclaimed quality carbon dioxide cargo contains impurities such as water, sulphur dioxide, etc., which can cause acidic corrosion or other problems.

APPENDIX B: Literature Review

RECORD ID	FOOTNOTE	AUTHORS / POCs	TITLE	PUBLICATION/ ORGANIZATION	DATE
ABS-1	15	Plevrakis, G., Koutsourakis, P., et al.	Setting the Course to Low Carbon Shipping: Zero Carbon Outlook	ABS	2022
ABS-2		Plevrakis, G., Sotirios, M., et al.	Setting the Course to Low Carbon Shipping: Pathways to Sustainable Shipping	ABS	2020
ABS-3			Offshore Production of Green Hydrogen	ABS	2022
ABS-4			ABS Advisory on Decarbonization Applications for Power Generation and Propulsion Systems	ABS	2021
ABS-5			Carbon Capture, Utilization and Storage	ABS	2021
ABS-6			Setting the Course to Low Carbon Shipping: 2030 Outlook, 2050 Vision	ABS	2019
DNV-1		Alvik, S., et al.	Energy Transition Outlook 2021	DNV	2021
DNV-2		Alvik, S., et al.	Energy Transition Outlook 2021: Executive Summary	DNV	2021
DNV-3		Alvik, S., et al.	Energy Transition Outlook 2021: Financing the Energy Transition	DNV	2021
DNV-4		Alvik, S., et al.	Energy Transition Outlook 2021: Technology Progress Report	DNV	2021
DNV-5			Alternative Fuels for Naval Vessels	DNV	2021
DNV-6		Alvik, S., et al.	Energy Transition Outlook 2022: Hydrogen Forecast to 2050	DNV	2022
DNV-7		Alvik, S., et al.	Energy Transition Outlook 2021: Maritime Forecast to 2050	DNV	2021
DNV-8		Alvik, S., et al.	Energy Transition Outlook 2021: Pathway to Net Zero Emissions	DNV	2021

RECORD ID	FOOTNOTE	AUTHORS / POCs	TITLE	PUBLICATION/ ORGANIZATION	DATE
DNV-9			IMO Update: Marine Environment Protection Committee (MEPC 77)	DNV	2021
DNV-10		Chryssakis, C., Tveit, O.	Alternative Ship Fuels - Status and Outlook	DNV	2022
LR-1			Techno-Economic Assessment of Zero Carbon Fuels	Lloyd's Register, University Maritime Advisory Services (UMAS)	2020
LR-2			Zero Emission Vessels: Transition Pathways	Lloyd's Register, University Maritime Advisory Services (UMAS)	2019
LR-3			First Movers in Shipping's Decarbonisation: A Framework for Getting Started	Lloyd's Register	2021
LR-4			IMO Implementation of IMO Instruments Eighth Session (III 8) Summary Report	Lloyd's Register	2022
LR-5	64		Zero-Emission Vessels by 2030. How do we get there?	Lloyd's Register, University Maritime Advisory Services (UMAS)	2017
GOV-1	9	Bernstein, L., Bosch, P., et al.	Climate Change 2007: Synthesis Report	IPCC	
GOV-2			Net Zero by 2050: A Roadmap for the Global Energy Sector	IEA	2021
GOV-3			Designation of North American Emission Control Area to Reduce Emissions from Ships	U.S. EPA	2010
GOV-4		McKoy, M.	NETL Carbon Storage Program	U.S. DOE NETL	2021
GOV-5		Lawson, A.	DOE's Carbon Capture and Storage (CCS) and Carbon Removal Programs	U.S. Congressional Research Service	2022

RECORD ID	FOOTNOTE	AUTHORS / POCs	TITLE	PUBLICATION/ ORGANIZATION	DATE
GOV-6			Carbon Capture, Transport and Storage: Supply Chain Deep Dive Assessment	U.S. DOE	2022
GOV-7			Technology Assessment: Ocean-Going Vessels (DRAFT)	CARB	2018
GOV-8			Air Resource's Board's Carbon Capture and Sequestration Program: 2016 Progress and Future Plans	CARB	2016
GOV-9			A Comparative Study of Existing Standards/Protocols for Carbon Capture and Sequestration to Inform Development of a Quantification Methodology	CARB	2016
GOV-10			2022 Scoping Plan Update (DRAFT)	CARB	2022
GOV-11	63	Monteiro, J.	CO_2ASTS - Carbon Capture, Storage, and Transfer in Shipping	European Union	2020
GOV-12			Reducing Shipping Greenhouse Gas Emissions: Lessons from Port-Based Incentives	International Transport Forum	2018
GOV-13	1	Faber, J., Hanayama, S., et al.	4th IMO Greenhouse Gas Study	IMO	2021
GOV-14	2		Initial IMO Strategy on Reduction of GHG Emissions from Ships	IMO	2018
GOV-15	4		Cutting Ships' GHG Emissions - Working Towards Revised Strategy	IMO	2022
GOV-16	7		Biden Administration Launches $3.5B Program to Capture Carbon Pollution from the Air	U.S. DOE	2022
GOV-17	12		Energy Efficiency Measures	IMO	no date
GOV-18	17		International Code of Safety for Ship Using Gases or Other Low Flashpoint Fuels (IGF Code)	IMO	

RECORD ID	FOOTNOTE	AUTHORS / POCs	TITLE	PUBLICATION/ ORGANIZATION	DATE
GOV-19	20	Baylin-Stern, A., Berghout, N.	Is Carbon Capture too Expensive?	IEA	2021
GOV-20	22	James, R., Keairns, D., et al	Cost and Performance Baseline for Fossil Energy Plants, Volume I: Bituminous Coal and Natural Gas to Electricity	U.S. DOE	2019
GOV-21	27		Large Pilot Testing of the MTR Membrane Post-Combustion CO_2 Capture Process	U.S. DOE	2018
GOV-22	38		Oxy-Combustion	U.S. DOE	no date
GOV-23			Reference Fluid Thermodynamic and Transport Properties Database	NIST	no date
GOV-24	75		Renewables - Global Energy Review 2021	IEA	2021
GOV-25			DOE Announces $75 Million to Accelerate Technologies for the Decarbonization of the Natural Gas Power and Industrial Sectors	U.S. DOE	2021
GOV-26	10		Climate Change 2021: The Physical Science Basis	IPCC	2021
NGO-1	16	Englert, D., Losos, A., et al.	The Potential of Zero Carbon Bunker Fuels in Developing Countries Volume I	The World Bank	2021
NGO-2			Catalysing the Fourth Propulsion Revolution	Intl Chamber of Shipping	2020
NGO-3		Norton, S., Hatley, J., et al.	A Perspective on IMO Efficiency Measures: Opportunities for Improvement	Blue Sky Maritime Coalition	2022
NGO-4		Smith, T., Baresic, D.	A Strategy for the Transition to Zero Emission Shipping: An Analysis of Transition Pathways, Scenarios, and Levers for Change	Zero Coalition	2021
NGO-5			A Zero Emission Blueprint for Shipping	Intl Chamber of Shipping, Ricardo	2021

RECORD ID	FOOTNOTE	AUTHORS / POCs	TITLE	PUBLICATION/ ORGANIZATION	DATE
NGO-6			Pathways to Net-Zero 2050 in the North American Marine Shipping Industry: Fuels and Propulsion Systems	Blue Sky Maritime Coalition	2022
NGO-7			Scope 1 Greenhouse Gas Emissions Calculation Methodology Recommendations	Blue Sky Maritime Coalition	2022
NGO-8			North American Waterborne Transportation Carbon Footprint	Blue Sky Maritime Coalition	2022
NGO-9	13		Fuelling the Fourth Propulsion Revolution: An Opportunity for All	Intl Chamber of Shipping	2022
NGO-10			Roadmap to Zero Emission from International Shipping	Japan Ship Technology Research Association	2020
NGO-11			Net-Zero Carbon Fuels Tech Team Roadmap	U.S. Drive	2021
NGO-12	18	Stena Bulk	Is Carbon Capture on Ships Feasible?	Oil and Gas Climate Initiative	2021
NGO-13		Comer, B.	Choose Wisely: IMOs Carbon Intensity Target Could be the Difference Between Rising and Falling Shipping Emissions in this Decade	International Council on Clean Transportation	2021
NGO-14	76		Aviation's Flight Path to a Net-Zero Future	World Economic Forum	2021
NGO-15	65		The Feasibility of Marine Carbon Capture	Oil and Gas Climate Initiative	2022
OTHER-1		Czermanski, E., Pawlowska, B., et al.	Decarbonization of Maritime Transport: Analysis of External Costs	Frontiers in Energy Research / Univ of Gdansk	2020
OTHER-2	66	Willson, P.	Evaluation of the Marine Application of Advanced Carbon Capture Technology	PMW Technology	2020
OTHER-3		Mulligan, T.	Technology: GHG Capture and Storage to the Fore	Offshore Engineer	2020

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OTHER-5		Schmauss, T., Barnett, S.	Viability of Vehicles Utilizing On-Board CO_2 Capture	American Chemical Society	2021
OTHER-6	68	Wermuth, N., Lackner, M.	The HyMethShip Project: Innovative Emission Free Propulsion for Maritime Applications	Graz Univ of Technology	no date
OTHER-7	46		Samsung Wins Approval for Carbon Capture System for LNG-Fueled Vessels	The Maritime Executive	2022
OTHER-8		Weissman, G., Folger, M.	Destination: Zero Carbon -- Three Strategies to Transform Transportation in America	Environment America, Frontier Group	2020
OTHER-9		Bothe, D., Janssen, M., et al.	CO_2 Emission Abatement Costs of Gas Mobility and Other Road Transport Options	Frontier Economics	2021
OTHER-10	67	Bell, M., Deyes, K., et al.	Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution	Frontier Economics, E4tech, UMAS	2019
OTHER-11		Perner, J., Unteutsch, M., et al.	The Future Cost of Electricity-Based Synthetic Fuels	Frontier Economics	2018
OTHER-12		Luis, P.	Use of Monoethanolamine (MEA) for CO_2 Capture in a Global Scenario: Consequences and Alternatives	Univ Catholique de Louvain	2016
OTHER-13		Kawamata, S., Watanabe, Y., et al.	Development of Onboard CO_2 Capture System	ClassNK Technical Journal	2022
OTHER-14			Carbon Capture - Case Study for a Ropax Ship	Shipbuilding News	2021
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OTHER-17		Buirma, M., Vleugel, J.	Ship-Based Carbon Capture and Storage: A Supply Chain Feasibility Study	Energies	2022
OTHER-18	61	Van den Akker, J.	Carbon Capture Onboard LNG Fueled Vessels: A Feasibility Study	Delft Univ of Technology	2017
OTHER-19	62	Stec, M., Tatarczuk, A., et al.	Reducing the Energy Efficiency Design Index for Ships Through a Post-Combustion Carbon Capture Process	International Journal of Greenhouse Gas Control / Institute for Chemical Processing of Coal	2021
OTHER-20		Hoeger, C., Burt, S., et al.	Cryogenic Carbon Capture Technoeconomic Analysis	Sustainable Energy Solutions	2021
OTHER-21	23	Bui, M., Adjiman, C.	Carbon Capture and Storage: The Way Forward	Energy & Environmental Science	2018
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OTHER-23			decarbonICE - Creating a Pathway to Carbon Negative Shipping	Bioenergy International	2019
OTHER-24			decarbonICE	decarbonICE	no date
OTHER-25		Chambers, S.	Dutch Boxship Makes History with CO_2 Capture and Storage Installation	Splash 247	2021
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OTHER-29			On-Board CO_2 Capture Method Could Make Long-Range Ships Carbon Negative	E&T News	2021
OTHER-30		Chambers, S.	Bilobe Tank Breakthrough Paves Way for Upscaling of Carbon Capture Projects	Splash 247	2020
OTHER-31		Gracia-Mariaca, A., Sastresa, E.	Review on Carbon Capture in ICE Driven Transport	Energies / Univ of Zaragoza	2021
OTHER-32		Chambers, S.	Scrubber 2.0: New Carbon Capture Funnel Unveiled	Splash 247	2020
OTHER-33			Beating the Heat - How Chemistry can Decarbonize the Economy and Stall Global Warming	American Chemical Society	2021
OTHER-34		Herzog, H.	An Introduction to CO_2 Separation and Capture Technologies	MIT Energy Laboratory	1999
OTHER-35			Navigate the Future with Confidence: Reducing GHG Emissions from Marine Propulsion	Winterthur Gas & Diesel	2021
OTHER-36		Izursa, J., Hanlon, E., et al.	Carbon Footprint of Biofuel Sugarcane Produced in Mineral and Organic Soils in Florida	Intelligentsia International, Univ of Florida	no date

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OTHER-39	5		U.S. Climate Envoy John Kerry Calls for 2050 Zero Emissions Target at IMO	Ship & Bunker	2021
OTHER-40	6		Congress Set to Discuss Maritime Decarbonization	National Law Review	2021
OTHER-41	8		Mitsubishi Shipbuilding to Test World's First Marine-Based CO_2 Capture System	Mitsubishi Heavy Industries	2020
OTHER-42	11		U.S. Nonroad Emissions	Transport Policy	no date
OTHER-43	14	Howard, G.	Carbon Capture Key to Net-Zero by 2050	Seatrade Maritime News	2022
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OTHER-45	24	Reddy, S., Yonkoski, J.	Fluor's Econamine FG Plus Completes Test Program at Uniper's Wilhelmshaven Coal Power Plant	Energy Procedia / Fluor Corp / Uniper Technologies	2017
OTHER-46	25		MHI's Carbon Capture Technology	Mitsubishi Heavy Industries	2016
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OTHER-49	29	Jain, R.	Bench-Scale Development and Testing of a Novel Adsorption Process for Post-Combustion CO_2 Capture	InnoSepra	2014
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OTHER-54	40		Technical Manual - Carbon Dioxide Storage Tank	Chart Industries	no date
OTHER-55	41		Ship Transport of CO_2	Mitsubishi Heavy Industries	2004
OTHER-56	43	Elhenawy, S., Khraisheh, M.	Metal-Organic Frameworks as a Platform for CO_2 Capture and Chemical Processes: Adsorption, Membrane Separation, Catalytic-Conversion, and Electrochemical Reduction of CO_2	Catalysts / Qatar Univ / Univ of Limerick	2020
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OTHER-63	52		Overview of "CC-Ocean" Project	Mitsubishi Heavy Industries	2021
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OTHER-73	71		DNV and PSE Report on Ship Carbon Capture and Storage	The Maritime Executive	2013
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OTHER-75	74		SNG-Synthetic Natural Gas	MAN Energy Solutions	no date
OTHER-76	78		Cummins Marine Products Guide	Cummins	2022
OTHER-77	79		Mitsubishi Diesel Engine Catalog	Mitsubishi	no date
OTHER-78	81		Atlas Copco Oil-Free Process Gas Compressors	Atlas Copco	no date
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