INSIGHTS INTO

ONBOARD CARBON CAPTURE

TABLE OF CONTENTS

OVERVIEW 1

Regulations and Carbon Policy 1

IMO Drivers for Onboard Carbon Capture 2

Mechanisms for Implementing Global Carbon Market 3

METHODS OF CARBON CAPTURE 4

Scrubbers 4

Carbon Capture using Solvents 5

Monoethanolamine (MEA) 6

Aqueous Ammonia 6

Potassium Hydroxide (KOH) 7

Sterically Hindered Amines 7

Piperazine 7

Ionic Liquids 7

Carbon Capture using Sorbents in Dry Scrubbers 7

Carbon Capture using Membranes 7

Cryogenic Carbon Capture 8

CARBON CAPTURE SYSTEM EFFECTIVENESS 9

Characteristics of Exhaust Gas 9

CAPTURED CARBON HANDLING AND STORAGE 11

Liquefied CO_2 11

Chemical Transformation 11

Energy Requirement Onboard 12

DOWNSTREAM CONSIDERATIONS 13

ONGOING ACTIVITIES 13

ABS SUPPORT 14

REFERENCES 15

LIST OF ACRONYMS 17

OVERVIEW

The International Maritime Organization (IMO) has proposed requirements for international shipping to reduce carbon intensity by at least 40 percent by 2030 and 70 percent by 2050 from the 2008 values.

These major reduction goals are driving the maritime industry to pursue various feasibility pathways for zero- and low-carbon fuels together with decarbonization technologies including carbon capture and the supporting systems required to store, transport and utilize or permanently sequester captured carbon.

Reports from the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) have stated that carbon capture efforts will likely be essential for global efforts of meeting net-zero carbon goals.

While the topic of carbon capture, utilization and storage (CCUS) encompasses many industries and technologies, this document highlights insights into onboard carbon capture systems in more detail, focusing on post-combustion capture technologies, the storage of captured carbon on board and the energy requirements to operate the additional equipment for carbon capture.

For more information about CCUS activities in general, see the 2021 ABS publication *Carbon Capture, Utilization and Storage*. For more information on global carbon capture efforts to support net-zero carbon goals, see the 2022 ABS publication *Setting the Course to Low Carbon Shipping: Zero Carbon Outlook*.

REGULATIONS AND CARBON POLICY

While onboard carbon capture may not yet be mandated by national or international policy, shipowners and charterers may see market or regulatory forces drive the adoption of onboard carbon capture solutions and the development of mechanisms to facilitate the trade of captured carbon.

Typically, when the adoption and implementation of new technologies or applications increases, the regulatory environment lags behind technology standardization.

IMO DRIVERS FOR ONBOARD CARBON CAPTURE

Current research projects that onboard carbon capture will play an important role in the decarbonization efforts of the shipping industry. So far, the IMO has focused on improving vessel efficiencies and the use of alternative fuels; however, carbon reduction may require onboard carbon capture as one of several tools to decarbonize shipping.

Onboard carbon capture and storage (CCS) may require significant additional capital and operating expenditure, especially where regulations and technologies are still developing, and the economic feasibility is still not fully understood. Onboard carbon capture is only one part of a multi-step process for atmospheric carbon reduction involving land-based and offshore carbon capture technology, temporary storage, offloading and discharging infrastructure, transportation by pipeline or vessel and utilization or geological sequestration. For onboard carbon capture to be considered viable, an economic feasibility case must be built.

MECHANISMS FOR IMPLEMENTING A GLOBAL CARBON MARKET

THE LONDON PROTOCOL AND LONDON CONVENTION

In the 41st consultative meeting of contracting parties to the London Convention, transboundary exports of carbon dioxide (CO_2) for the purpose of carbon sequestration were provisionally allowed under certain circumstances. Since 2006, the London Protocol has provided a basis for international environmental law allowing carbon storage beneath the seabed. The London Protocol prohibits the export of wastes, including CO_2, however in 2009 an amendment allowed sequestration projects to be shared across national boundaries. This amendment is not yet in force but a further amendment in 2019 allows provisional application of the 2009 amendment by flag Administrations indicating their intent to provisionally apply the 2009 amendment, before entry into force. The London Protocol and London Convention can facilitate the international transport of CO_2 by ship, increase availability of portside infrastructure for CO_2 loading, unloading and subsequent discharge of carbon captured on board vessels.

The growth of the sequestration market can spur ship-based carbon capture offloading solutions. Storing CO_2 on board in tanks and offloading at port is a technical challenge that needs to be resolved, as current regulations and infrastructure are in the nascent stage.

ISO TECHNICAL COMMITTEE FOR CARBON DIOXIDE CAPTURE, TRANSPORTATION, AND GEOLOGICAL STORAGE

The ISO Technical Committee ISO/TC 265 "Carbon dioxide capture, transportation and geological storage" publishes standards which historically have focused on industrial sectors such as power, cement, iron and steel production, where carbon capture is more mature than offshore applications. While onboard carbon capture may not be specifically referenced in the standards, they may apply to any post-combustion CO_2 capture system, for example:

- ISO 27919-1:2018 Carbon Dioxide Capture – Part 1: Performance evaluation methods for post-combustion CO_2 capture integrated with a power plant
- ISO/TR 27912:2016 Carbon Dioxide Capture Systems, Technologies and Processes

IMO SUPPORT FOR RECEPTION FACILITIES

IMO recognizes that reception facilities are crucial for MARPOL implementation. In March 2018, the IMO Maritime Environmental Protection Committee (MEPC) adopted the consolidation guidance for port reception facility providers and users. Currently, the regulation does not specify CO_2 handling from ship-based capture, which should be addressed in future versions of the regulation as greater deployment of the technology occurs. Additionally, custody transfer of CO_2 from the ship to the final onshore handler, i.e., measuring and recognizing collected and transferred CO_2, needs to be addressed in future monitoring, reporting and verification standards and regulations.

OTHER MARKET DRIVERS

Captured CO_2 can also be a commodity for sale. Currently, captured CO_2 is used in the food and beverage industry, in the oil and gas industry for enhanced oil recovery (EOR) and other commercial applications. Further development of the CO_2 value chain can help push the case for carbon capture. For example, the captured CO_2 can be used to create renewable fuels. As the CO_2 commodity market grows, onboard carbon capture may be incentivized.

To create an incentive for greater deployment of onboard carbon capture, the new technology return on investment should be evaluated. Furthermore, from an industry perspective, the regulatory and policy framework for carbon trading needs to mature. Some of the policy levers that can be used effectively to stimulate the application of onboard carbon capture include:

1. A carbon tax on the amount of CO_2 emitted from vessels; in such a scenario, every operator would be incentivized to reduce their carbon footprint.
2. The creation of carbon credits and trading such as the EU Emission Trading Scheme (ETS); when there is a cap-and-trade program. Carbon credits could be valuable tradeable commodities. With greater credit value comes higher incentives for the operator to capture CO_2 for sale in the market.
3. The U.S. 45Q Tax Credit system for sequestered carbon includes possible tax credits of:
   a. $35 per ton for EOR
   b. $50 per ton for geologically sequestered carbon without EOR activity

METHODS OF CARBON CAPTURE

There are many potential methods for the removal of carbon, shown in Figure 1. For onboard applications, pre-combustion and oxy-combustion carbon capture methods may be applied or considered to improve the effectiveness of post-combustion carbon capture methods. Further information on pre-combustion and oxy-combustion is available in the 2021 ABS publication Carbon Capture, Utilization and Storage.

Post-combustion carbon capture on board ships involves cleaning exhaust gases before release, typically by installing equipment within or near the vessel exhaust stack.

The methods for post-combustion shipboard carbon capture being considered by the maritime industry include chemical absorption, membrane separation and cryogenic carbon capture technologies. These can either be retrofitted on existing ships or fully integrated into new ship designs.

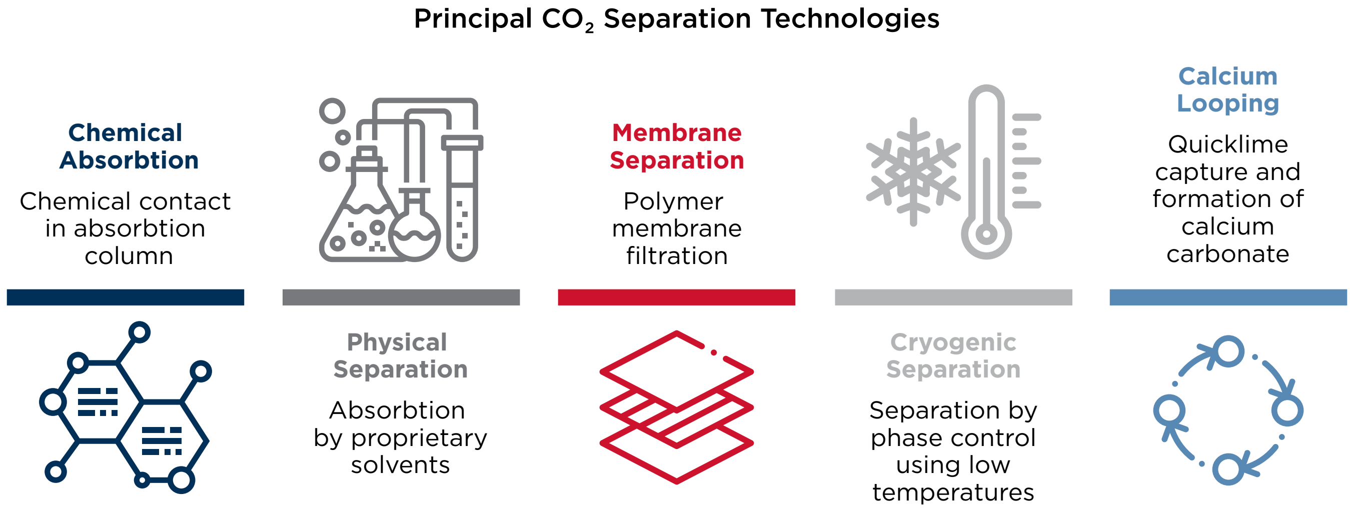

Figure 1: Types of Carbon Capture Systems

While Figure 1 shows various types of carbon capture systems, the unique criteria for operating on ships may allow only a few types to be feasible. In addition to cost considerations, when installed on board ships, the systems are also sensitive to size, weight and power limitations. The optimization of various onboard system architectures can result in more effective solutions. Carbon capture methods specifically discussed here include chemical absorption, membrane separation and cryogenic separation.

SCRUBBERS

Following the IMO regulations and goals for addressing carbon emissions, investigations are ongoing to apply or adapt scrubber technology for part of the CO_2 capture process.

Scrubbers can be characterized by functional categories: wet scrubbers, dry scrubbers or hybrid scrubbers. The majority of marine sulfur oxide (SOx) scrubbers are wet scrubbers using an open loop process and are regulated under MARPOL Annex VI Regulation 4 as equivalent technologies for low sulfur fuel. There are dedicated IMO Exhaust Gas Cleaning System guidelines for the design, certification and approval of SOx scrubbers including discharges to air and water. This technology may be adapted for the cleaning and cooling of exhaust gases prior to passing to the absorber and desorber parts of a chemical absorption carbon capture system.

For general information about the installation of exhaust gas cleaning systems, see the ABS publication *Practical Considerations for the Installations of Exhaust Gas Cleaning Systems.*

CARBON CAPTURE USING SOLVENTS

Depending on the fuel type and exhaust quality, the first step in many exhaust gas purifying systems for carbon capture is to reduce the impurities and gas species including SOx, Particulate Matter (PM), heavy metals, ash and nitrogen oxides (NOx) that may be present in the exhaust gas. Onboard carbon capture systems may utilize wet scrubbing in the exhaust gas quenching/cooling stage and then be arranged using an absorber unit where the solvent extracts CO_2 from the exhaust stream. The CO_2-rich solvent is then sent to a desorber, or stripping, unit to both separate CO_2 from the solvent and recover the solvent for reuse. Depending on the type of solvent used, they may degrade over time at various rates and require replenishment or replacement, while the spent solvent or residue requires proper handling and disposal.

Supporting systems for the main process stages include water vapor removal, heat exchangers for temperature and constituent phase control, blowers or pumps for circulation, or other systems to achieve the desired quality of captured CO_2.

See Figure 2 for a generic onboard carbon capture and storage system using solvents. The 2022 ABS publication *Setting the Course to Low Carbon Shipping – Zero Carbon Outlook* includes various concept design arrangements of onboard carbon capture using monoethanolamine (MEA) solvent systems for 50 percent and 90 percent carbon capture on a bulk carrier, tanker and a containership, respectively. The arrangements conceptually show the estimated sizes of the carbon capture systems with explanatory information regarding ship routing, power requirements and system capacities.

General Considerations for Retrofitting Carbon Capture Systems

- Capture system retrofit planning, including space constraints and power availability
- Procurement and suitability for vessel
- Engineering, including material compatibility, system configuration and vessel integration, and class and statutory approval
- Installation, including onboard or onshore (in construction) preparation, supporting structures, electrical equipment, piping, ship stability/ equipment weight
- Management and unloading arrangements for stored carbon/CO_2
- Storage and handling of solvent/sorbent chemical
- Commissioning, including calibration of monitoring and control systems, functional testing, and performance evaluations for the complete system
- Operation, including manning and crew intervention, safety function, and maintenance and repair of the system.
- Design and construction to recognized standards and engineering fundamentals
- Procedures and training for crew, including onboard operations, offloading and maintenance
- Control systems design and operation, including cyber safety

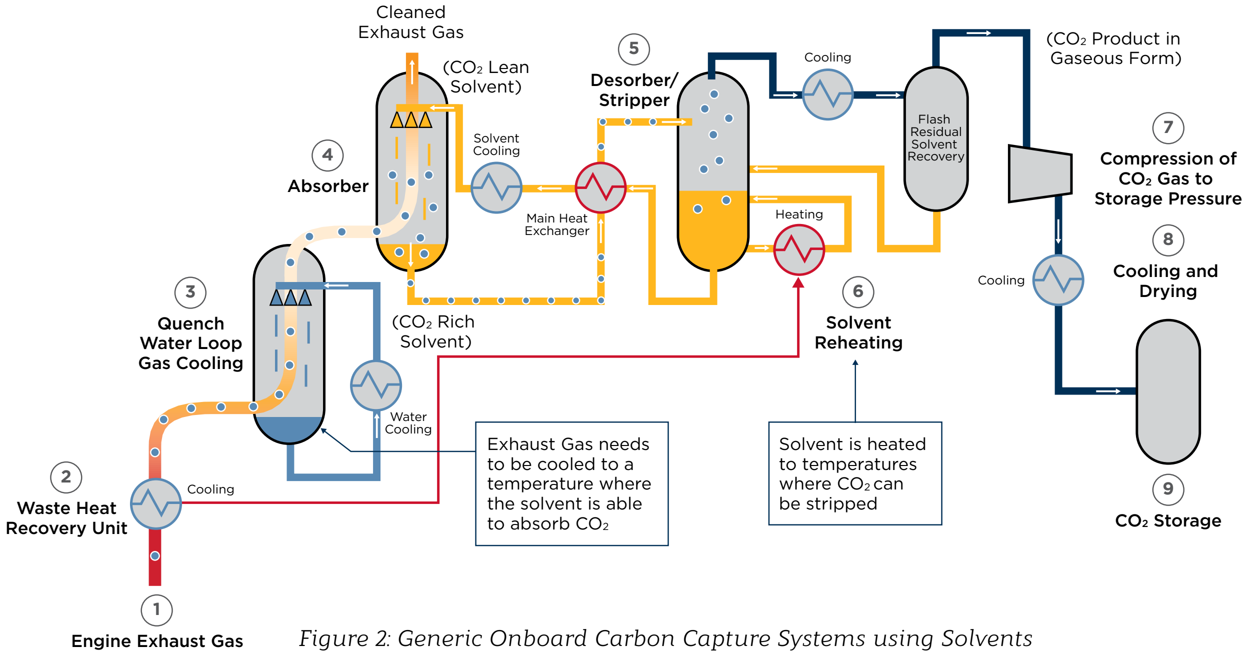

Figure 2: Generic Onboard Carbon Capture Systems using Solvents

Considerations for Amine or Chemical Solvent Systems

- Required energy for solvent regeneration
- Available power supply and footprint for supporting systems
- Energy optimization for system integration
- Proper supply and disposal or recycling of chemicals for CO_2 capture
- Procedures and crew training for the carriage, handling, loading and discharge of hazardous chemicals
- Ammonia hazards
  - Toxicity, acute
- MEA hazards
  - Toxicity, skin irritant
  - Flammability
  - Corrosiveness
- KOH hazards
  - Corrosiveness
  - Reactiveness

Solvents work as aqueous carriers that absorb excess CO_2 molecules from the gas stream and can be composed of a combination of liquefied chemicals. Already used in land-based applications, the technical aspects of carbon absorption using solvents such as MEA, diethanolamine (DEA) and methyldiethanolamine (MDEA), commonly referred to as amines, are mature and well understood. These three amines exhibit similar characteristics and are generally referred to here simply as MEA. Although handling MEA on land is well understood, it can present a new challenge for handling and storing on board ships. Other solvents introduced here for chemical carbon absorption or direct carbon separation are aqueous ammonia, potassium hydroxide (KOH), sterically hindered amines, piperazine and ionic liquids.

Based on the criteria for the system or operational constraints, various system architectures and solvent types can be used to achieve different carbon capture and energy efficiencies or size/weight system optimizations. Typically for solvent systems, energy requirements are highest for the energy needed (heat of reaction) for CO_2 absorption, heating the CO_2-rich amine solution to the regenerator temperature, or producing steam needed for solvent regeneration.

All solvent-based carbon capture systems may require careful consideration of amine or chemical handling needed for operations. For example, solvents that need periodic replenishment or replacement may have specific requirements for the volumes or supply of extra solvent, spent chemical or residue handling and discharge procedures.

MONOETHANOLAMINE (MEA)

MEA-based gas cleaning is a well-proven and commercially available method used in land-based applications. Studies have shown that MEA solvent blends were more effective at carbon capture than other solvent blends. However, it should be considered that high efficiency solvents may require high energy input for regeneration.

MEA-based solvents may require a high amount of thermal energy for regeneration (i.e., energy input for the solvent recovery process in the desorber/stripping unit). MEA can also be corrosive to materials and degrade over time. However, the extensive industry experience using MEA allows it to often be used as a benchmark comparison for various alternative carbon capture solvent options.

MEA exists in a liquid state inside the closed loop absorber and desorber solvent systems and must be periodically replenished or replaced. It is hazardous when in contact with the eyes or ingested and is also a skin and inhalant irritator. It is combustible and corrosive, so it is recommended to be stored in a closed container with storage temperature below the known flash point of 86° C. MEA storage containers must be kept dry and away from heat sources. It is classified as a corrosive material, so local and international regulations may provide guidance on proper storage and handling.

AQUEOUS AMMONIA

Aqueous ammonia has alternatively been considered a feasible solvent for carbon capture systems due to lower energy requirements. However, ammonia is in high demand in the fertilizer industry, and therefore can be more expensive than other solvents. It is classified as a hazardous chemical, with the disadvantages of using ammonia-based systems including risk of human exposure and environmental pollution.

POTASSIUM HYDROXIDE (KOH)

An alternative solvent to MEA and ammonia is KOH, which has comparable performance to other solvents, but may require additional considerations for chemical handling. KOH can be stored as a powdered solid or dissolved in an aqueous solution. Inside the carbon absorption and desorption units, KOH is used as an aqueous solution. In the liquid state, the solution must be stored in a dry, closed container that is resistant to corrosion. This chemical is classified as non-combustible but should be protected from release or exposure to other substances it may react with.

STERICALLY HINDERED AMINES

Water-soluble amines known as sterically hindered amines or formulated amines (characterized by a molecular shape where the nitrogen atom of the amine is partially shielded and thus more difficult for large molecules to react with) can show potential for reducing energy expenditure when used as a solvent for carbon capture systems. The use of these chemicals could reduce regeneration costs, but they may require larger absorption and desorption units.

PIPERAZINE

Another chemical compound, piperazine, has been investigated as an option for carbon capture due to its strong CO_2 affinity and high absorption rate. However, this molecule has limited solubility in water, so its use is limited to blends with other compounds.

IONIC LIQUIDS

Research into the solubility and absorption potential of ionic liquids (chemical salt solutions that are liquid at room temperature) shows an ability to improve the efficiency of existing carbon absorption systems. Ionic liquid research is related to molecular electrostatic interactions. Ionic liquids were found to be effective in electrochemical reduction of CO_2, and therefore may be able to capture carbon at a high uptake efficiency.

CARBON CAPTURE USING SORBENTS IN DRY SCRUBBERS

Sorbents are used in dry scrubber systems to purify exhaust gas streams. Sorbents are solid carriers that are either suspended or scattered within the scrubber. There are many chemicals that can be used in a dry scrubber system, and it is also possible to integrate them with wet scrubber systems for post-processing of the exhaust gas stream. The use of dry scrubbers is not common in the marine environment. This is most likely due to low technical maturity, non-regenerative sorbent characteristics and outperformance by wet scrubbers when comparing efficiency, cost and maintenance requirements.

Although dry scrubbers are not fully industry-ready at this time, further research on solid carriers and dry scrubbers could address the efficiencies of existing technologies.

CARBON CAPTURE USING MEMBRANES

Membranes can be implemented as a physical filtration system to absorb various impurities, including carbon gas. Conventional membrane technology consists of filters specific to molecule sizes and can require significant input pressure.

Gaseous membrane CO_2 filters are made of a semi-permeable fabric that allows selected molecules to pass through while restricting the flow of others. The efficiency of these systems is negatively affected by the presence of other gasses such as NOx and SOx groups, and moisture.

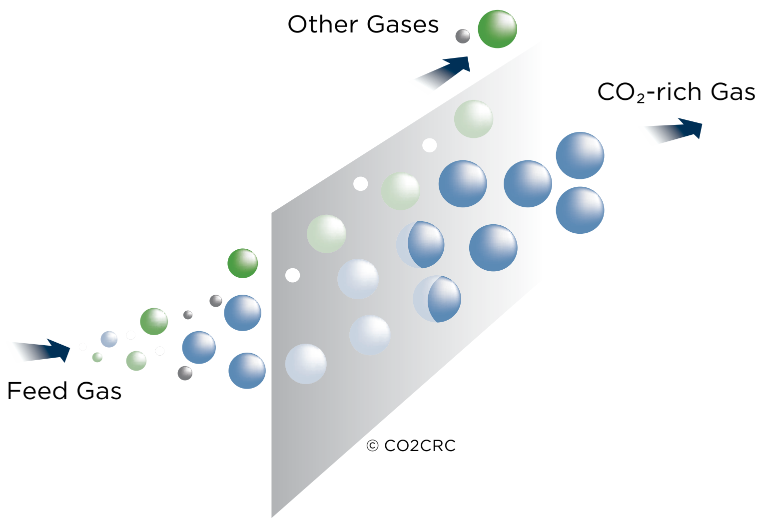

Figure 3: Gaseous Membrane Filtration

Advanced membrane technology may also use solid carriers (sorbents) bonded to the surface of a filter to encourage chemical or electrical CO_2 separation. These are novel and emerging technologies which involve less commercially available systems but may show potential for the future of carbon capture on board ships.

When used in an exhaust gas stream, effective membrane filtration often relies on the use of chemicals with an affinity to carbon to separate the particles in the stream. Effective membranes should have high CO_2 permeability, high selectivity of CO_2 to nitrogen (i.e., high ratio of CO_2 to nitrogen permeability) and be stable at high temperatures and various chemical states.

Some available membranes with these characteristics are polymer-based, with membrane materials consisting of cellulose acetate, polymides, polysulphone and polycarbides. Polymeric coatings may be more cost efficient but can be less effective at separating carbon than cellulose acetate or polycarbonate coatings. Testing of various membrane materials for carbon capture produced promising results but found membranes can be unstable over long periods and may require frequent maintenance, treatment or replacement.

Considerations for Membranes

- Membrane filter replacement and maintenance
- Membrane CO_2 permeability and efficiency
- Exhaust gas stream impurities and partial concentrations
- If applicable, required power input for electrochemical modulation
- Required power for gas pressure control

Emerging membrane technologies for carbon capture are investigating the use of electrochemical interactions to enhance their effectiveness, known as electrochemically mediated carbon capture. This process uses a chemical known as benzoquinone to increase membrane carbon affinity when exposed to an electric potential. The capital expenditure for this method can be high due to its novelty and the lack of commercial availability. However, it shows potential to reduce the space requirements for carbon capture technology and limit the operational expenses.

CRYOGENIC CARBON CAPTURE

Cryogenic carbon capture is a process in which carbon is separated from exhaust gas by controlling phase changes via temperature and pressure (thermodynamic) modulations. The effectiveness of cryogenic carbon capture relies on the various chemicals found in the gas stream. The process involves cooling exhaust gas to the solidification point of CO_2 (-100 to -135° C). Where conventional distillation processes may prefer liquid products for ease of handling, it has been shown in various studies that vapor-to-solid separation can be more energy-effective. Using the CO_2 solidification extraction method to extract gases, including NOx and SOx, results in two exhaust gas streams; one consisting of pressurized pure CO_2 (99 percent or higher), and another comprised of the remaining contents in the original exhaust at ambient pressure, as shown in Figure 4. This system can be installed on existing ships with a relatively small footprint connected to an exhaust gas input and a power source. The extreme temperatures necessary for the cryogenic carbon capture process require the integration with other systems on board to optimize the heat exchange process.

This method is achieved primarily by a network of heat exchangers, the specific architecture of which can significantly improve the energy efficiency of the installed system. It is estimated that this process can reduce the energy consumption of carbon capture by 50 percent when compared to solvent-based carbon capture systems. While cryogenic carbon capture systems appear to have promising advantages over other systems, research is still ongoing to develop, optimize and implement for application onboard ships.

Due to the low temperature requirements for cryogenic carbon capture, they may be of interest to vessels carrying liquefied natural gas (LNG) (which is stored at temperatures as low as -163° C). There may be opportunities for the LNG cryogenic systems to work harmoniously with the cryogenic carbon capture systems to gain additional efficiencies.

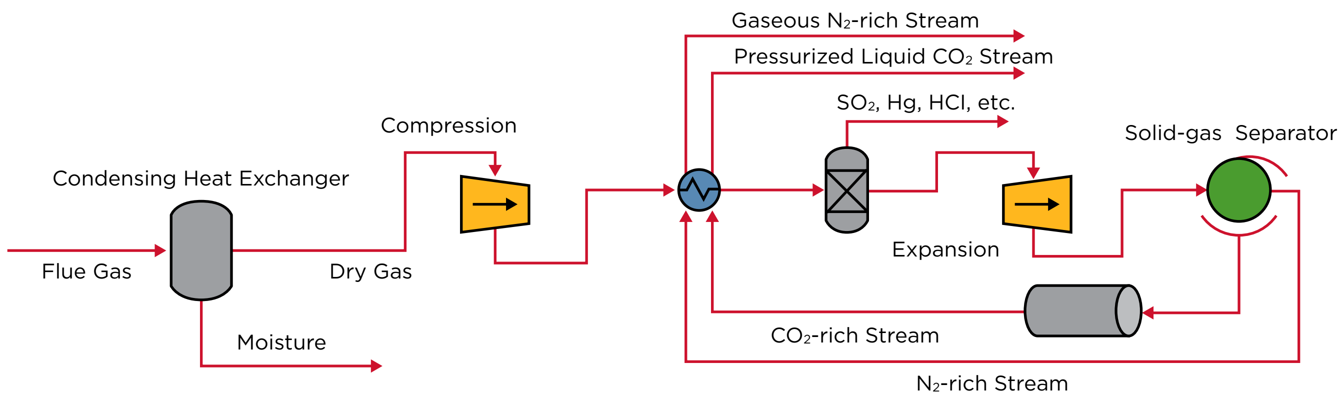

Figure 4: Typical Cryogenic Carbon Capture process

CARBON CAPTURE SYSTEM EFFECTIVENESS

Typically, carbon capture systems may not effectively capture all carbon from the exhaust stream. While it is possible to capture higher percentages of carbon from the exhaust, more input energy and/or additional equipment may be disproportionately required. Operators must therefore decide the quantity of carbon intended to be captured based on emission reduction goals and the feasibility of additional equipment, storage space and supporting systems for onboard capture systems.

The effectiveness of carbon capture systems to purify exhaust gas varies widely, depending on the type of capture system, rate of absorption, capture system size, fuel type, fuel consumption rate and the amount of CO_2 concentration in the exhaust gas.

Considerations for Cryogenic Carbon Capture

- Available power on board for heat exchange network and compression
- Opportunities to integrate with existing heat exchange systems (especially for low temperatures such as LNG)
- Implications of pure (up to 99 percent) CO_2 supply depending on the end-quality needed or desired (e.g., storage requirements or opportunity for resale)

CHARACTERISTICS OF EXHAUST GAS

The primary use of CO_2 in the marine industry is for EOR. It is also transported as cargo for use in the food and beverage industry, which requires the CO_2 to be free of impurities. The type and level of impurities that originate from the exhaust gas that may be present alongside captured carbon needs to be considered within the system design, particularly for the impact of impurities on process equipment and storage tank materials. The contents of exhaust gas from the combustion reaction varies depending on numerous parameters, including the type of fuel, type of engine, combustion process, engine load, steady state or transient loads, ambient conditions and installed emission control technologies.

Due to fuel chemical composition, lighter fuel oils tend to result in an exhaust gas with a higher concentration of CO_2 and less SOx and PM when compared to heavy fuel oil (HFO). The consumption of diesel/marine gas oil (MGO), liquefied petroleum gas (LPG), ethane and LNG may offer some benefits of reduced emissions or pollutants, but all hydrocarbon fuels emit CO_2 when combusted. In all cases, the actual exhaust emissions depend on a variety of factors. For simplicity, the amount of CO_2 emitted is often based on default values linked to the fuel's carbon content (in nondimensional units of m/m), energy content (lower calorific value in kJ/kg) and typical engine fuel consumption data. These parameters are represented by the CF carbon factor value (in units of tons of CO_2 per ton of fuel) used in the IMO's Energy Efficiency Design Index (EEDI) and other regulations, including the Energy Efficiency Existing Ship Index (EEXI) and fuel oil Data Collection System (DCS). Table 1 shows some of the principal fuel characteristics for marine fuels and cargoes used as fuel.

Table 1: Carbon Content of Various Fuels

Type of Fuel	Identification	Description	Lower Calorific Value (kJ/kg)	Carbon Content m/m	CF (tCO2/ t fuel)
Diesel/Marine Gas Oil	ISO 8217 Grades DMX through DMB	Distillate petroleum marine fuels of various specified characteristics	42,700	0.8744	3.206
Light Fuel Oil	ISO 8217 Grades RMA through RMD	Residual petroleum marine fuels with kinematic viscosities (at 50° C) equal to or lower than 80 mm^2/s	41,200	0.8594	3.151
Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	Residual petroleum marine fuels with kinematic viscosities (at 50° C) higher than 80 mm^2/s	40,200	0.8493	3.114
Liquefied Petroleum Gas (LPG)		Gaseous fuel primarily composed of propane (C_3H_8) or butane (C_4H_{10})	46,300 (propane)	0.8182	3.000
			45,700 (butane)	0.8264	3.030
Ethane		Gaseous fuel primarily composed of ethane (C_2H_6)	46,400	0.7989	2.927
Liquefied Natural Gas (LNG)		Gaseous fuel primarily composed of methane (CH_4)	48,000	0.7500	2.750
Ethanol		Liquid fuel primarily composed of ethyl alcohol (C_2H_5OH)	26,800	0.5217	1.913
Methanol		Liquid fuel primarily composed of methyl alcohol (CH_3OH)	19,900	0.3750	1.375

CAPTURED CARBON HANDLING AND STORAGE

As vessel size, speed and consequently fuel consumption increase, carbon stack emissions can also increase. Total carbon emissions (and therefore total captured carbon) from a vessel over one voyage therefore can depend on the type of fuel consumed, vessel size, weight, engine rating and performance, voyage speeds, environmental conditions and route length. For example, highly effective carbon capture systems would require more storage capacity and handling equipment, however, frequent discharges or shorter routes may not require as much carbon storage capacity or handling equipment.

As technology develops to support carbon capture requirements, additional considerations for the application of various equipment in a marine environment is necessary. When planning to capture carbon and store it onboard, ship designers, owners and operators should consider system operation and maintenance, available space, required power, availability of auxiliary systems, necessary controls and any potential economic tradeoff can impact the feasibility of technology on different ships.

More information about the conditioning processes of CO_2 purification, dehydration or liquefication is provided in the ABS publication *Carbon Capture, Utilization and Storage* applicable to the onboard handling and storage of CO_2.

Once captured, there are several options to store carbon until it is ready to be discharged. In general, CO_2 can be stored in gaseous or liquid forms by compressing or liquefying the gas to cryogenic conditions or can be chemically transformed through a reaction process to a product that is easier to handle.

LIQUEFIED CO_2

To maximize the capacity of CO_2 storage in limited space, liquefaction on ships may be the most appropriate solution considering space requirements as well as the ease of handling a liquid cargo.

Liquefied CO_2 can be stored in pressurized and insulated tanks while on board to maintain cryogenic conditions. Pressurized tanks can handle boil-off from liquid CO_2 up to certain design pressures, where pressure relief and boil-off gas reliquefaction has typically then been implemented. Type C liquefied gas tanks, as detailed by the IMO's International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), are the current marine standard for pressurized CO_2 storage.

Although research is currently underway for the use of other classes of tanks, using Type C is common industry practice due to the relatively high pressures required for storage of liquefied CO_2. Care should be given to the purity of stored CO_2 within Type C tanks, as impurities can cause corrosion in the storage system. More information on tanks for gaseous cargoes can be found in the ABS *Advisory on Gas and Other Low Flashpoint Fuels* and the ABS *Guidance Notes on Strength Assessment of Independent Type-C Tanks*.

CHEMICAL TRANSFORMATION

Methods of onboard storage that involve absorption or chemical transformation can produce a substance that is easier to manage and store than gaseous or liquefied CO_2. This may involve the production of a solid substance which could increase market value. However, vessel stakeholders considering these methods of onboard storage should keep in mind additional reactant chemical supply, handling and storage, reactor equipment, as well as the processing rates and storage capacity on board for the produced chemical.

One method of chemical transformation uses chemical absorption and subsequent reactions to produce calcium carbonate from the captured gas. In this process, CO_2 is absorbed by sodium hydroxide (NaOH, i.e., caustic soda) to form sodium carbonate. This product is then treated with a calcium oxide (CaO, or quicklime) solution to form solid calcium carbonate (CaCO3) and regenerate the NaOH. $CaCO_3$ is commonly known as soda ash, and forms a powder or small pellets, depending on the concentration of the reactants.

NaOH is a solid at room temperature, so pressurized and climate-controlled storage containers may not be necessary. However, it is corrosive to metal and damages skin on contact. Safety measures should be taken when handling the chemical.

$CaCO_3$ is a white powder of small crystals and is not considered hazardous by the Occupational Health and Safety Association (OSHA). It is not flammable or corrosive, but it is a strong oxidizing agent and acid.

This method to extract CO_2 from the exhaust gas allows sodium hydroxide to be recirculated and for the captured CO_2 to be stored as a solid soda ash product. NOx, SOx and other acidic gases are also absorbed by NaOH. This may offer small reductions in the cost of solution degradation and space required for temporary storage while underway. The cost of this additional precipitate can be offset by marketing produced $CaCO_3$ to the paper, construction or plastic industries. $CaCO_3$ typically has greater commercial value than CO_2, which could significantly offset the operational expenditures of this system.

ENERGY REQUIREMENT ON BOARD

The onboard energy requirements for carbon capture systems depend on the type and size of the system, the flow rate of exhaust gas into the system and the target efficiency for carbon removal.
The energy requirements for carbon capture can increase immensely as the target capture rate rises.

Energy for carbon capture is required for various purposes, including electrical or thermal inputs to manage CO_2 or other product processing. Heat exchangers, chemical regeneration activities, steam generation, pumps, compressors, condensers, evaporators, reactors and liquefaction systems may be required for various carbon capture and handling architectures.

It is also critically important to consider that as more energy is required in addition to typical vessel loads, onboard engines and auxiliary generators may also need to increase power generation, resulting in an increased amount of exhaust emissions. For this reason, system power consumption is directly related to carbon capture effectiveness and is an essential consideration for the overall feasibility of the carbon capture system on board.

Consideration is also to be given to the energy requirements of the carbon storage systems, as applicable. For example, CO_2 liquefaction equipment can significantly increase the required energy supply.

This could be a drawback for liquefaction of captured CO_2 on board. However, energy and space requirements are closely tied and often inversely proportional. If liquefaction is not available, the space requirement for temporary onboard storage of gaseous CO_2 can increase prohibitively.

Considerations for Storing Captured CO_2 On Board

- Moisture content and contaminants in captured CO_2 stream and corrosive effects on system
- Requirements to maintain pressure and temperature of captured CO_2 (i.e., compressed, liquefied) within specified limits
- Sufficient power and capacity available for handling and storage systems on board
- Volume and mass of captured CO_2 per route or voyage for storage space requirements
  - Foundational support for added equipment
  - Vessel strength and stability with added equipment
- Measuring and verifying amounts captured, stored and offloaded
- Locations, frequency and rate of discharge or transfer
- Additional chemical supply systems and equipment for onboard generation of calcium carbonate (if applicable)
- Potential leakage or release of CO_2; the dense gas does not readily disperse in the same way lighter gases do
  - CO_2 Detection and alarms
  - Minimizing non-welded connections for leak protection
  - Emergency procedures and training for storing CO_2 on board and related incidents

Considerations for Required Onboard Energy

- Impact of capture and storage system on operational power loads
- Required captured CO_2 purity and capture rate
- Handling additional emissions generated due to higher energy requirement from CO_2 capture system
- Opportunity for energy efficiency improvements through heat exchangers or integration with existing onboard systems

DOWNSTREAM CONSIDERATIONS

While not discussed in detail herein, downstream considerations are critical to support the global impact of local carbon capture efforts. For example, the choice of arranging long-term carbon sequestration versus selling the captured carbon may influence the long-term intent of capturing carbon.

The economic drivers for carbon capture could offer opportunities to resell captured products and avoid potential carbon taxes. Additional infrastructure may be necessary to offload CO_2, evaluate delivered CO_2 properties, measure delivered amounts of CO_2 and purify or process the delivered CO_2 if necessary. Land-based or offshore infrastructure for carbon storage and transportation may have an impact on the scale of carbon capture efforts and will also be necessary to support the eventual sequestration or utilization of the captured carbon.

Pipelines for CO_2 transport currently exist to support EOR operations. Alternatively, gas carriers can be used to transport CO_2. The choice involves understanding the economic and technical feasibility of gas carriers and pipelines, depending on the expected distance transported, volumes and international export requirements.

Downstream Considerations for CO_2

- Offloading arrangement procedures and training for crew
- Available offload and storage facilities at ports and terminals
- Metering for carbon trade efforts
- Market value of captured CO_2
- Opportunities for carbon taxes, levies or trading schemes
- Life-cycle impact of captured CO_2
  - Permanent sequestration can reduce atmospheric greenhouse gas (GHG)
  - Resale and use of captured CO_2 in industry may result in re-emission into atmosphere

The processing of CO_2 is supported by technologies developed in coal fired plants and other land-based operations. One option is to resell a pure CO_2 stream to support the production of other fuels (e.g., the production of synthetic fuels such as e-methanol, e-LNG or other e-fuels), use for EOR or processed as various solids used in other manufacturing industries. These market options have the potential to mitigate operating expenses (OPEX) of onboard carbon capture. Not only does this make the IMO carbon capture goals more achievable, but it makes research and development of new and efficient technologies more attractive.

ONGOING ACTIVITIES

The development of carbon capture technologies is actively ongoing, with emerging efforts focusing on the feasibility of carbon capture on board ships for a wider range of operations.

Some efforts focus on modifying existing onboard systems for carbon capture. For example, Langh Tech, a sister company of Langh Ships, is researching and testing modifications to SOx scrubbers to capture carbon from exhaust gas streams. While the presence of more CO_2 in the process water was expected to be higher, the process was found to be reasonable and operating expenses were not significantly impacted. Research continues at Langh Tech to optimize the scrubber efficiency and the effort needed for process water regeneration.

Other ongoing activities involve implementing new technologies on board.

A memorandum of understanding (MOU) was signed in 2021 by TECO 2030 ASA, Chart Industries and PMW Technologies to develop carbon capture technologies for ships and store liquefied captured carbon. The system uses cryogenic carbon capture methods and expects to achieve a highly pure liquefied CO_2 cargo. The continual research into this method further offers the potential that cryogenic carbon capture will play a role in onboard technologies in the future.

Deltamarin, a Finland-based ship designer, completed a case study in 2021 for carbon capture using a solvent scrubber system incorporated with LNG fueling arrangements on a roll-on/roll-off passenger (ro/pax) ferry. The design incorporated a Wärtsilä exhaust treatment to capture CO_2. The LNG ferry was chosen for the study because they operate on fixed routes and captured carbon can be frequently discharged onshore, as shown in Figure 5. This can provide benefits such as less carbon storage required as well as inherent benefits of heat exchange, heat recovery, and heat sinks when incorporated with the LNG fuel management systems.

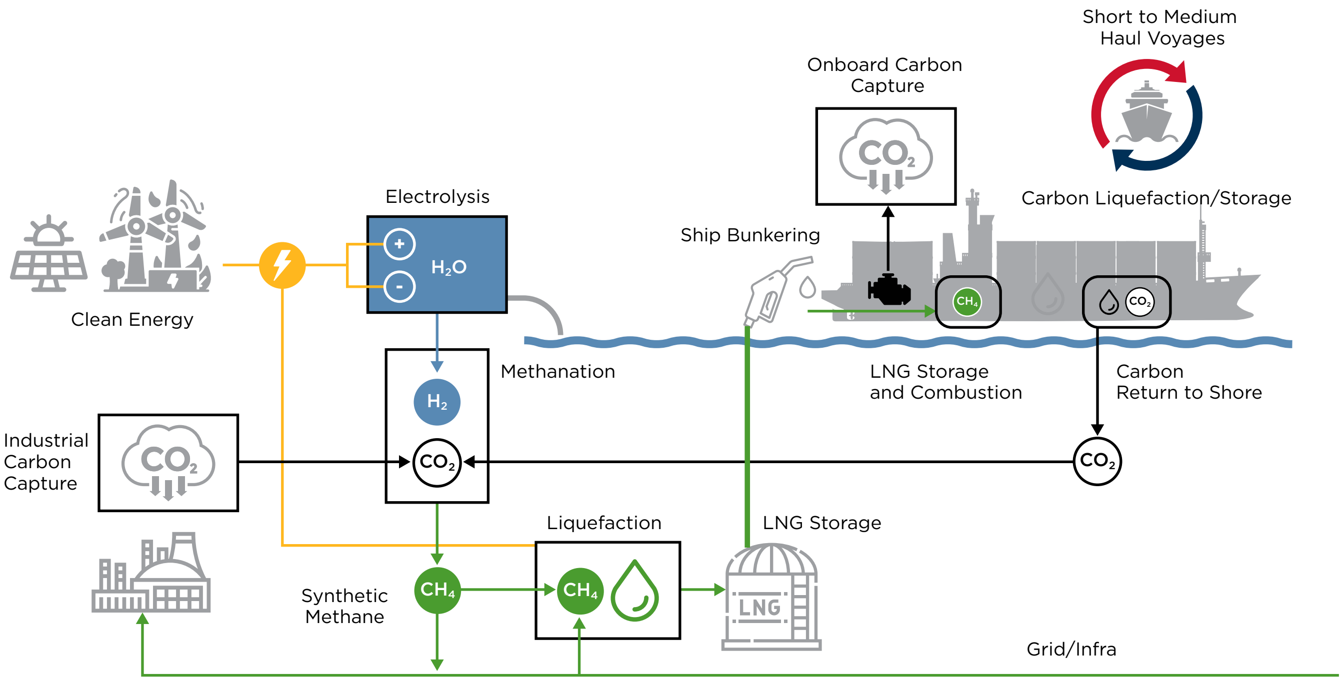

Figure 5: Case Study for CO_2 Carbon Capture on an LNG-fueled RoPax Ferry

Value Maritime is in collaboration with Carbon Collectors to create a conceptual design study for a fleet of carbon neutral tug vessels fueled by MGO. The project is described by Value Maritime as a true 100 percent recycling operation that will capture all the CO_2 exhaust from the ship and will investigate solutions for unloading and permanent sequestration. The design plan includes construction in 2024, and fleet operations in 2026 using the carbon capture systems.

ABS SUPPORT

ABS is equipped to assist owners, operators, shipbuilders, designers and original equipment manufacturers as they consider practical implications and risk assessments of onboard carbon capture. Services offered include:

- Marine vessel design and construction support for classing vessels and offshore facilities
- Techno-economic analyses
- Certification based on public ISO standards
- Novel Concept Qualification
- Qualifying new carbon capture technology
- Risk assessment and Hazard Review
- Vessel/fleet benchmarking and identification of improvement options
- EEDI and EEXI verification and identification of improvement options
- Optimum voyage planning
- Contingency arrangement planning and investigations

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LIST OF ACRONYMS AND ABBREVIATIONS

ABS	American Bureau of Shipping
$CaCO_3$	calcium carbonate
CaO	calcium oxide, e.g., quicklime
CCUS	carbon capture, utilization and storage
CCS	carbon capture and storage
CO_2	carbon dioxide
DCS	Data Collection System (IMO)
DEA	diethanolamine
EEDI	Energy Efficiency Design Index (IMO)
EEXI	Energy Efficiency Existing Ship Index
EOR	enhanced oil recovery
EU	European Union
GHG	greenhouse gas
HFO	heavy fuel oil
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
KOH	potassium hydroxide
LNG	liquefied natural gas
LPG	liquefied petroleum gas
MDEA	methyldiethanolamine
MEA	monoethanolamine
MEPC	Marine Environment Protection Committee (IMO)
MGO	marine gas oil
NaOH	sodium hydroxide, e.g., caustic soda
NOx	nitrogen oxides
OPEX	operational expenditure
OSHA	Occupational Health and Safety Association
PM	particulate matter
SOx	sulfur oxides

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