Marine Carbon Capture
Techno-economic Analysis

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Acronym List

A3C	Advanced Cryogenic Carbon Capture
ABS	American Bureau of Shipping
BTU	British Thermal Unit
$CaCO_3$	Calcium Carbonate
CaO	Calcium Oxide
$Ca(OH)_2$	Calcium Hydroxide
CAPEX	Capital Expenditure
CCF	Capital Charge Factor
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilization and Storage
CII	Carbon Intensity Indicator
CO_2	Carbon Dioxide
EEDI	Energy Efficiency Design Index
EPA	Environmental Protection Agency
FEED	Front End Engineering and Design
GHG	Greenhouse Gases
GJ	Giga Joule
HSM	Hardin Street Marine
IMO	International Maritime Organization
kW	Kilowatt
kW-hr	Kilowatt Hour
LCE	Life Cycle Engineering
LNG	Liquified Natural Gas
LSFO	Low Sulfur Fuel Oil
MGO	Marine Gas Oil
MEA	Monoethanolamine
MMBtu	One Million British Thermal Units
MT	Mega Tonne
M/V	Motor Vessel

MW	Megawatt
NETL	National Energy Technology Laboratory
NOx	Oxides of Nitrogen
O&M	Operations and Maintenance
psid	Pressure per Square Inch Differential
RFI	Request for Information
SEEMP	Ship Energy Efficiency Management Plan
SO_2	Sulfur Dioxide
TEA	Techno-Economic Analysis
UK	United Kingdom
ULSD	Ultra Low Sulfur Diesel

Acknowledgements:

The authors wish to thank the US Maritime Administration for supporting this work. They also wish to thank the following companies for their assistance in providing carbon capture removal technology and vessel information needed to support the calculations described in this report: Aramco, PMW Technology, Seabound, InnoSepra, Hardin Street Marine LLC (“HSM”), and International Seaways, Inc.

Disclaimer:

Opinions expressed in this report are the author’s own and do not represent the views of any other entity. The findings in this report are not to be construed as an official Maritime Administration position. Trade names cited in this report do not constitute an official endorsement or approval of the use of such equipment.

1 Executive Summary

The first phase of this Shipboard Carbon Capture study was to perform a "Technology Review" of capture technologies and capture studies specific to shipboard applications. As a follow-on to the technology review, a techno-economic analysis (TEA) for shipboard carbon capture was performed. The TEA assessed the technical and economic viability of shipboard post-combustion carbon capture and storage. This report summarizes the results of the techno-economic analysis.

A techno-economic analysis is, as the name implies, a combination of a technical analysis of a process or technology followed by an economic analysis. The technical analysis for this study included such things as quantifying utility requirements (shaft power, heat, water, etc.) as well as quantities, weights, and volumes of feedstocks, process products, and consumables. The technical analysis was followed by an economic analysis where capital, operating and maintenance costs were estimated. The economic analysis resulted in two Figures of Merit (Cost of CO_2 Captured and Cost of CO_2 Avoided) that were used to estimate the economic viability of each process and compare different processes.

Shipboard carbon capture involves running exhaust gas from a ship engine(s) and auxiliary power equipment through a CO_2 capture system. Treated exhaust gas with a significant reduction of CO_2 is discharged to the ambient atmosphere while captured CO_2 is compressed, liquefied, and stored aboard (solvent, sorbent, and cryogenic technologies) or retained on the sorbent (calcium looping technology) until the captured CO_2 can be unloaded when the ship docks. Four carbon capture technologies (solvents, sorbents, cryogenic, and calcium looping) and two different ships were included in the study. Membranes were initially included but eventually excluded since they do not perform well with low CO_2 concentrations typical of this application (4 to 8% CO_2 concentrations in exhaust gas).

M/V Map Runner was one of the vessels selected to include in this study. The Map Runner is an inland waterway pusher/tug. The second vessel included in the study was the M/V Seaways Brazos. The Brazos is an ocean-going crude oil tanker. Inclusion of these two vessels allowed the study to compare and contrast the differences between a smaller vessel with less horsepower that docks frequently versus a larger vessel with greater horsepower that transits longer between docking.

Based on the techno-economic analysis, it is estimated that shipboard CO_2 capture and storage can be performed for a cost ranging from approximately \$150 to 200/tonne CO_2 captured depending on the ship and the capture technology. The Cost of CO_2 Avoided is higher, ranging from approximately \$175 to \$250/tonne CO_2 avoided, depending on the technology selected. These estimates are believed to be accurate to within about 30% for the assumed modeling parameters. It is important to note that certain items not included within this study may impact these calculations, such as lost revenue due to downtime for installation and construction of the CCS system, incremental shipboard labor required to operate the CCS system, offloading the captured CO_2 and fresh/spent sorbent, taxes, and CO_2 capture credits.

2 Introduction

This study performed a techno-economic analysis (TEA) for shipboard carbon capture using post-combustion capture. One definition of a TEA is described below:[1]

"Techno-economic analysis is a method of analyzing a process or product's technical and economic performance; it uses mathematical modelling to estimate capital cost, operating cost, and revenue. Additionally, techno-economic models can be used to identify the most efficient and cost-effective technology, materials, fuels, feedstocks.

The TEA provides an overview of key indicators in a concise and visually coherent form, providing you with information that will help you guide your R&D efforts and will provide valuable data for your business case and investors."

A block flow diagram of the system to be analyzed is shown in Figure 1. Exhaust gas from the ship engine(s) and auxiliary power equipment is treated in the CO_2 capture system. Treated exhaust gas with a significant reduction of CO_2 is discharged to the ambient atmosphere. Captured CO_2 is compressed, liquefied, and stored aboard ship until it can be unloaded when the ship docks. Four carbon capture technologies and two different ships are studied.

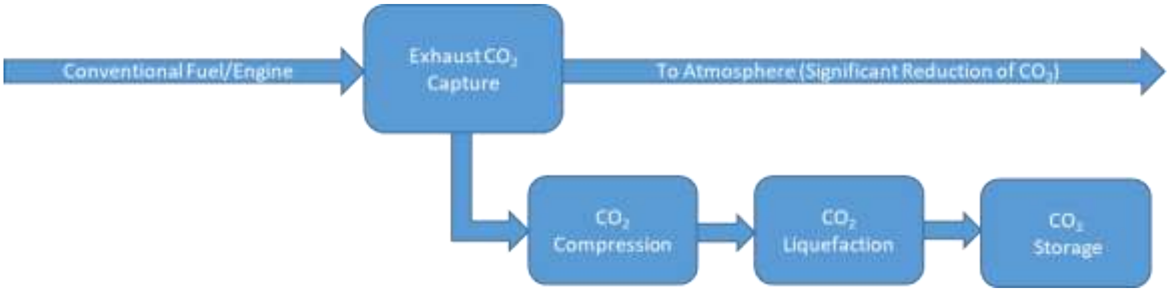

Figure 1 – Block Diagram of CO_2 Capture, Compression, Liquefaction, and Storage System

A techno-economic analysis is, as the name implies, a combination of a technical analysis of a process or technology followed by an economic analysis. The technical analysis includes such things as quantifying utility requirements (shaft power, heat, water, etc.) as well as quantities, weights, and volumes of feedstocks, process products, and consumables. The technical analysis is followed by an economic analysis where capital, operating and maintenance costs are estimated. The economic analysis results in a Figure of Merit that is used to estimate the economic viability of the process or compare different processes as done for this study. For this study, the Figures of Merit are Cost of CO_2 Captured and Cost of CO_2 Avoided. The TEA provides an overview of important process and economic indicators in a concise and visually coherent form, providing information that will help guide R&D efforts and provide valuable data for investors and business owners.

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[1] Sustech Innovation. (2022, February 18). *What is a techno-economic analysis, and why should you do yours as soon as possible?* https://www.linkedin.com/pulse/what-techno-economic-analysis-why-should-you-do-yours-.

Prior to this TEA, a Marine Carbon Capture Technology Review was completed by the team that includes significant background information .[2] Only a few introductory paragraphs of that report will be repeated here. The reader is referred to the complete report for additional background information.

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.[3] *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 study provides economic data to assist in the decision whether or not to apply carbon capture technologies to shipboard decarbonization and if so, which technology to use. There appears to be no clear winner regarding the capture technology of choice so it is likely several will need to be demonstrated to obtain detailed data and experience for evaluation.

The ships studied include the Map Runner (Figure 2) which is an inland waterway pusher/tug and the Seaways Brazos (Figure 3) which is an ocean-going 158,000 tonne deadweight crude oil tanker.

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[2] "Marine Carbon Capture Technology Review", MARAD Cooperative Agreement #693JF72150005, Document #DOC-G0036-0006, October 24, 2022, prepared by Life Cycle Engineering and Process & Equipment Development Corp., https://www.maritime.dot.gov/sites/marad.dot.gov/files/2022-11/LCE%20CCS%20Study%20Final%20Report%2024%20Oct%202022.pdf

[3] 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

Figure 2 – Map Runner

Figure 3 – Seaways Brazos

The four capture technologies include solvents, sorbents, cryogenic, and calcium looping. Membranes were initially included but eventually excluded since they do not perform well with low CO_2 concentrations typical of this application (4 to 8% CO_2 concentrations in exhaust gas). A capture efficiency requirement of 90% was specified for all the technology developers. It was beyond the scope of this study to evaluate the impact of lower or higher capture efficiency on the economics.

3 Technical Analysis - Ships, Capture Systems, Compression and Liquefaction, and Storage Details

The first phase of this Shipboard Carbon Capture study was to perform a "Technology Review" of capture technologies and capture studies specific to shipboard applications.[2] Specific steps for the second phase (TEA phase) of this project included:

- Select the specific vessels for the analysis. One inland (Map Runner) and one sea-going (Seaways Brazos) vessel were selected. Details in section 3.1.
- Select the carbon capture technologies to be evaluated and identify developer(s) for each of these technologies. Details in section 3.2.
- Prepare a Request for Information (RFI) to be sent to the capture technology developers to obtain cost and performance information for each capture technology for each of the vessels to be analyzed. The RFI is included in Appendix A.
- Utilize the capture technology developer supplied information to determine the auxiliary power requirement and ultimate capacity of the capture system to treat the base exhaust gas plus the exhaust gas from auxiliary power generation. Details in section 4.2.
- Utilize the capture technology developer supplied information other reference materials to estimate the capital cost of all the system equipment. Details in section 4.3.
- Utilize information from section 4.2 to calculate Operating and Maintenance Costs. Details in section 4.4.
- Utilize the capital and O&M cost from section 4 to calculate the Cost of CO_2 Captured and Cost of CO_2 Avoided. Details in section 4.6.

A simple block model of the CO_2 capture, compression (not required for Calcium Looping), liquefaction (not required for Calcium Looping), and storage is shown in Figure 1.

3.1 Vessel selection

Two types of vessels were selected for this evaluation to provide a different perspective for looking at the opportunity to insert carbon capture. While the insertion and marine engineering challenges for each of these vessels will be different, the assessment for the weight, size, and cost impact will be similar. The first was selected from the vessels operating on the inland waterways of the U.S, which accounts for over 20 percent (9.3 m tonne) of the U.S. vessel CO_2 emission inventory.[4] The second was

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[4] "North American Waterborne Transportation Carbon Footprint," Blue Sky Maritime Coalition, July 2022.

a U.S. flagged deep-seagoing vessel (a crude oil tanker) that has been modeled by others for carbon capture.

3.1.1 Inland water vessel

The U.S. inland waterway vessel fleet poses an interesting challenge for insertion of carbon capture as a solution. According to a recent study by Vanderbilt University, there are over 3,600 inland towboats in service from the smaller fleet boats to the largest line haul boats.[5] These vessels are designed with shallow draft. All are currently fueled with ultra low sulfur diesel (ULSD) fuel and powered by diesel engines ranging from a few hundred horsepower to up to 12,000 horsepower. Unlike their deep-sea counterparts, these vessels move their cargo in specially designed barges that are also shallow draft.

The towboat selected for this evaluation was HSM's M/V Map Runner which is a fleet boat. The vessel is 65 feet long, 26 feet wide, and is 120 Gross Tons. HSM chose the M/V Map Runner since it is used for fleeting barges and has high operating hours. The workboat is equipped with Caterpillar 3412E 720 HP twin engines for main propulsion and their generator is a Caterpillar 3304 65 kW engine. It is a shallow draft vessel. Figure 4, courtesy of HSM, depicts the Map Runner outboard profile which shows the limited deck space and shallow draft design. HSM provided the detailed operational modeling and fuel consumption information used for this analysis.

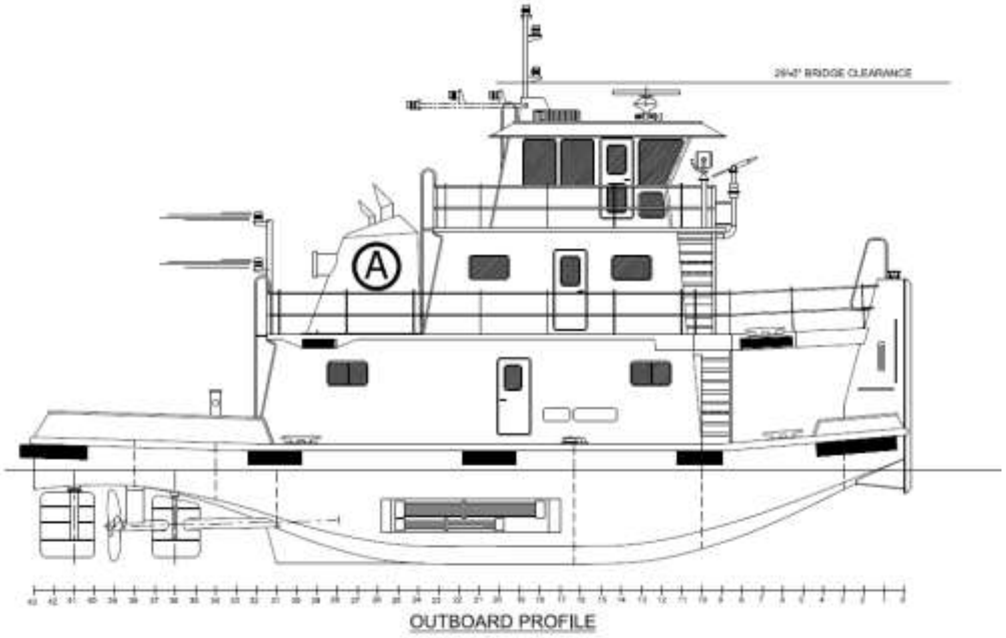

Figure 4 – M/V Map Runner – Outboard Profile

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[5] "Decarbonization of the Inland Waterway Sector in the United States, ABS and Vanderbilt University, September 2021.

3.1.2 Sea-going vessel

The sea-going vessel selected for this evaluation was the Seaways Brazos. The Seaways Brazos is a crude oil tanker operated by International Seaways, Inc. It has an overall length of 274 meters and beam of 48 meters. Its main propulsion engine is a DOOSAN Model 6S70MC-C 18,215 kW slow speed engine. It also has a Yanmar generator engine. The ship currently runs on low sulfur fuel oil (LSFO) at-sea and switches to marine gas oil (MGO) when in port or in restricted areas. This vessel was chosen to provide CO_2 modeling because of its representative 2-cycle slow-speed main propulsion heavier fuel engine. International Seaways, Inc. provided the details of engine operational detail and fuel requirements used in this analysis.

3.2 Carbon Capture Technologies

3.2.1 Cryogenic

Information used in this study for the cryogenic capture technology was provided by PMW Technology (https://www.pmwtechnology.co.uk/company/Background) and is extracted from a document provided pursuant to the Request for Information (RFI) shown in APPENDIX A. A technology update is being developed by PMW Technology that was not available during the preparation of this report. Details of the new concept were provided by PMW and is included in APPENDIX B.

PMW Technology is a small process development company established in 2016 to develop and exploit a novel physical carbon capture process based on desublimation of carbon dioxide from gas streams at low temperatures. That process is called Advanced Cryogenic Carbon Capture (A3C) and is covered by patents internationally.

The A3C technology is based on the proven concept of separating carbon dioxide by freezing it out of a gas mixture. In a typical implementation, the separation process follows a gas pre-treatment step which removes water and contaminants from the exhaust gases. The separation stage produces a stream of carbon dioxide gas which is liquefied by the conventional compression and cooling steps. The liquid carbon dioxide is then stored in insulated tanks. The overall process is illustrated in Figure 5. The first stage of the process is a conventional scrubber that washes traces of soot and soluble acid gases, such as sulphur dioxide, from the exhaust gas. This stage may use an open or closed water cycle to wash and cool the gases. The washwater is treated to remove any suspended contaminants with dosing as necessary.

The second stage, which may form part of the first column, is a cooled quench section using circulation of chilled water. This stage cools and reduces the water vapour content of the gases to very low levels. Any residual soot or soluble contaminating gases are further reduced in this stage. The final step in the pre-treatment is the cooler-drier moving bed heat exchanger. This heat exchanger uses the cold low carbon dioxide content exhaust gases from the separation stage to cool the cleaned inlet gases using an intermediate bed of fine metallic or ceramic beads. The remaining small amount of water vapour in the inlet gases is condensed or frosted onto the bed material and evaporated into the lean exhaust gas stream. The inlet gases leave this stage at around -100°C (-148°F). The separation process uses a further *moving bed heat exchanger to cool the cold inlet gases so that most of their carbon dioxide content is deposited as a frost on the circulating metallic or ceramic beads.*

The beads move slowly counter to the inlet gases and once they pass out of the contact region, they are warmed sufficiently to sublime the carbon dioxide frost off the bed at around -75°C (-100°F). The warmer bed material is elevated to the top of the heat exchanger where it is cooled to the inlet condition over refrigerated heat exchange surfaces. This temperature is as low as necessary (typically - 125°C, -195°F) to reduce the carbon dioxide concentration in the outlet gases to less than 10% of the level at the inlet.

The cold low carbon dioxide gases leave the separation stage for energy recovery in the cooler-drier. Despite the pre-treatment stages there will remain low levels of trace contaminants such as unburned hydrocarbons, nitric oxide and carbon monoxide. However, these gases have too low a vapour pressure to condense in the range of temperatures in the separation stage and pass through the capture process unchanged to be discharged to atmosphere.

The cooling necessary for the process is provided by a nitrogen cycle refrigeration system. This technology is conventional e.g., for boil off gas re-liquefaction on liquefied natural gas (LNG) carriers. In the A3C application conditions are less demanding and by rejecting heat at low temperatures to warm the packed bed to recover the carbon dioxide, the compressor energy consumption is radically reduced. This close integration of refrigeration reduces the energy consumption of the process to less than 33% of the amine process, to well below 1GJ/ton compared with around 3 GJ/ton.

The process feasibility study supported by the UK government was undertaken with academic and industrial partners and published in 2019. A parallel research project proved the process at laboratory scale was completed in 2020. This was followed by the construction of a pilot rig with a capacity of 50kg CO_2 *per day which demonstrated the system early in 2023. Negotiations to build a prototype unit sized for a 1 MW engine are currently in progress.*

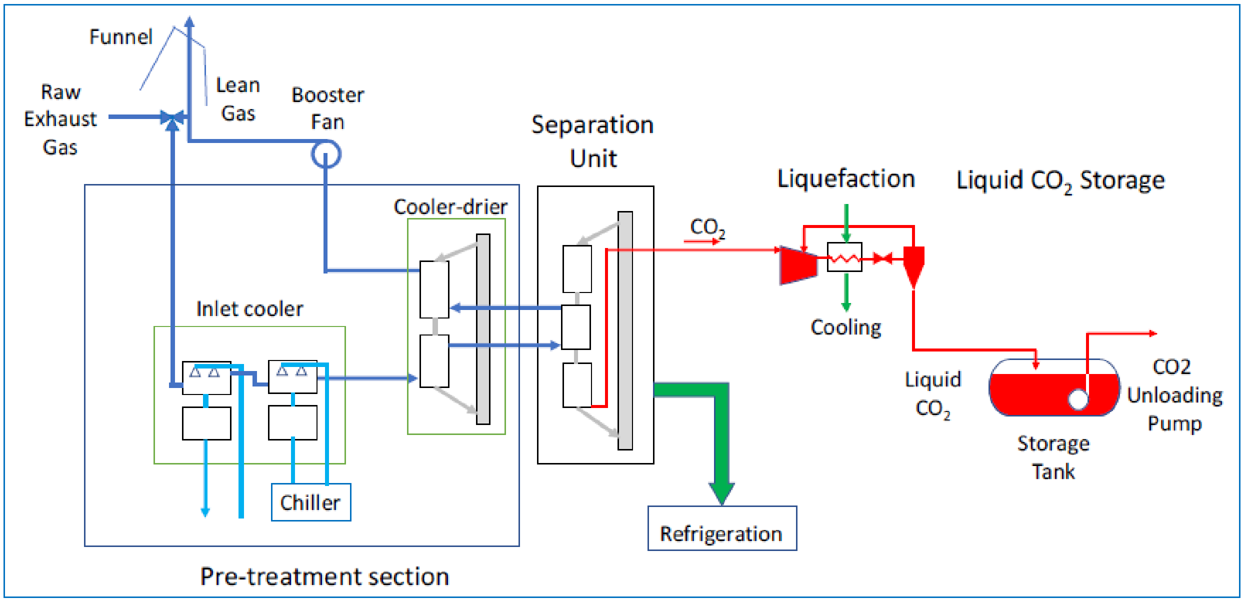

Figure 5 – Outline of A3C process followed by CO_2 liquefaction and storage

3.2.2 Calcium Looping

Information used in this study for the calcium looping technology was provided by Seabound (https://www.seabound.co/) and is extracted from documents provided by Seabound pursuant to the RFI included in APPENDIX A. A technology update is being developed by Seabound that was not available during the preparation of this report. Details of the new concept were provided by Seabound and is included in APPENDIX B.

3.2.2.1 Introduction to Seabound

Seabound is a climate technology startup on a mission to decarbonize shipping. Seabound is developing ship-based carbon capture equipment to reduce up to 95% of CO_2 *emissions from existing or newbuild vessels. Founded in Oct 2021, Seabound has so far completed a successful sea trial of a pilot system to capture* CO_2 *at 1 tonne/day on a 3200 TEU container vessel, signed 6 letters of intent with major shipowners to purchase early systems, and secured backing from leading investors including Y Combinator, Lowercarbon Capital, and Eastern Pacific Shipping Ventures. Seabound's ambition is to install carbon capture equipment onboard 1,000 vessels by 2030 and 10,000+ vessels by 2040 to capture 100M+ tons of* CO_2 *per year by 2040.*

3.2.2.2 Technology Overview

Seabound is developing a decoupled onboard and onshore approach to carbon capture that leverages calcium looping technology (see Figure 6). Calcium looping is a cyclical, two-step process between carbonation and calcination. First, lime in pebble form is loaded onto a vessel that has an installed Seabound carbonator. In the carbonation step, the exhaust gas is routed through the carbonator in which its constituent CO_2 *reacts with and binds to CaO contained within the reactor to form calcium carbonate (*$CaCO_3$*). The* $CaCO_3$ *is then ejected from the reactor and temporarily stored onboard the vessel until it reaches port for off-loading and post-processing. The second calcination step occurs on land, if at all:* $CaCO_3$ *is heated in a zero-emissions lime calciner to regenerate the CaO and separate it from* CO_2*. The CaO can be re-loaded onto another vessel with a carbon capture system and the* CO_2 *sold as a feedstock for new products (e.g. synthetic fuels, chemicals) or transported for geological sequestration. Alternatively, the* $CaCO_3$ *can be sold directly as a feedstock to the lime or construction industries.*

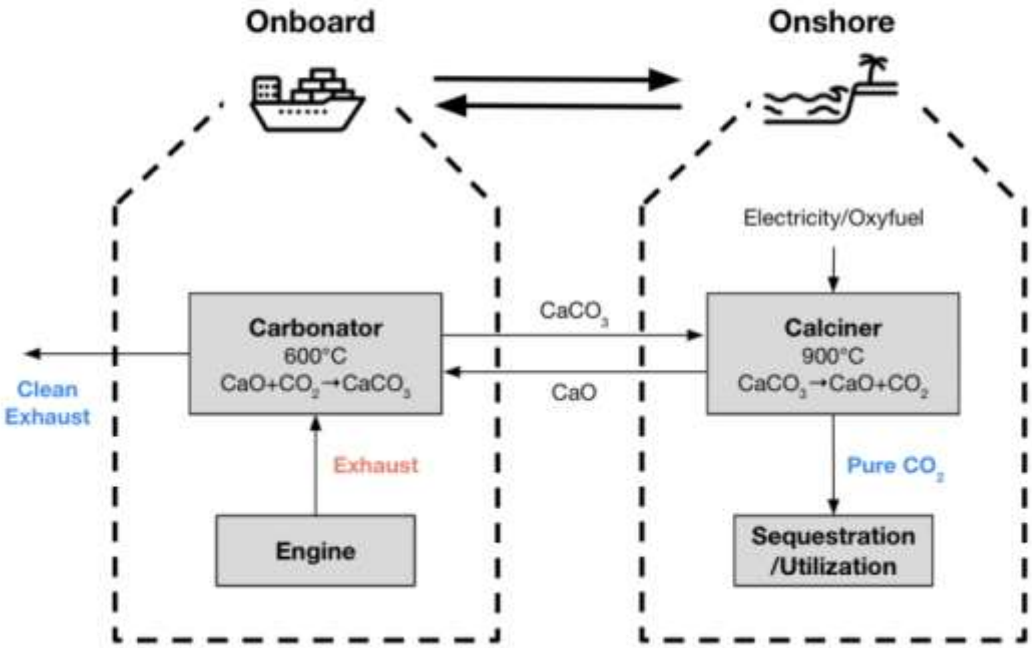

Figure 6 – Seabound SBCC process decoupled between onboard and onshore components

The use of calcium looping for ship-based carbon capture has multiple advantages:

1. *Lowered CAPEX compared to conventional carbon capture technologies (e.g. amines): Calcium looping enables the decoupled process of carbonation and calcination to take place on ships and on land respectively, which reduces onboard equipment size and CAPEX, reduces the total number of calciners required and moves the energy-intensive calcination step to land.*
2. *Negligible energy consumption for the capture process onboard: The carbonation reaction is exothermic - it releases rather than consumes energy, which has the potential for waste heat recovery to reduce additional fuel consumption.*
3. *Minimal operational complexity:* CO_2 *is stored in the stable, solid form of* $CaCO_3$ *(i.e. limestone) for easy handling, eliminating the need for* CO_2 *compression/liquefaction and refrigerated/pressurized tanks onboard.*
4. *No toxic chemicals: CaO and* $CaCO_3$ *are non-toxic materials that are safe for both the environment and crewmembers.*
5. *Potential for ocean* CO_2 *removal: longer-term,* $CaCO_3$ *and residual CaO could potentially be discharged directly overboard to support ocean alkalinity enhancement (pending further environmental studies and regulatory approval).*

3.2.3 Solvent

Figure 7 – SuezMax

Information used in this study for the solvent capture technology was provided by StenaBulk (https://www.stenabulk.com/) in the form of two public papers and also a public report by the U.S. Department of Energy.[6,7,8] Stena Bulk, founded 1982, is one of the world's leading tanker shipping companies transporting crude oil and refined petroleum at sea.

StenaBulk is conducting a Front-End Engineering & Design (FEED) study titled "Realizing Maritime Carbon Capture to demonstrate the Ability to Lower Emissions" (ReMarCCAbLE) to apply a solvent carbon capture system on a SuezMax oil tanker (Figure 7).[9] StenaBulk did not respond directly to the RFI request but rather the project team scaled information from the public documents to complete this TEA.

It is noted that the StenaBulk report indicated it is only possible to capture 8% of the CO_2 with the available heat energy from the propulsion engines. They indicated this low capture w/o additional thermal energy is a result of the efficient, slow-speed, two-stroke engine.

3.2.3.1 Technology Overview

Solvent gas separation technologies are common in the process industry and all have similar flow diagrams. Figure 8 shows a flow diagram for the solvent system planned by StenaBulk for the SuezMax.[7] Exhaust gas from the main engine, generator, and boiler will enter the capture system flowing through a Waste Heat Recovery Unit (WHRU) and then into a Quench unit for further cooling and removal of SO_2 and NOx. Cooled exhaust gas will then enter the suction of a booster blower to provide pressure to push the exhaust gas through the Absorber and Water Wash. The solvent absorbs CO_2 from the exhaust gas in the Absorber. The Water Wash is necessary to scrub the exhaust gas of any solvent aerosol carryover. Solvents are generally toxic materials and it is essential to limit emission of solvent materials. CO_2 is absorbed by the solvent in the Absorber vessel.

Rich solvent (solvent containing CO_2) flows out of the bottom of the Absorber and is pumped through a rich solvent-to-lean solvent (low CO_2 concentration) heat exchanger where the rich solvent is preheated and the lean solvent cooled. The pre-heated rich solvent enters the top of the Stripper where it is

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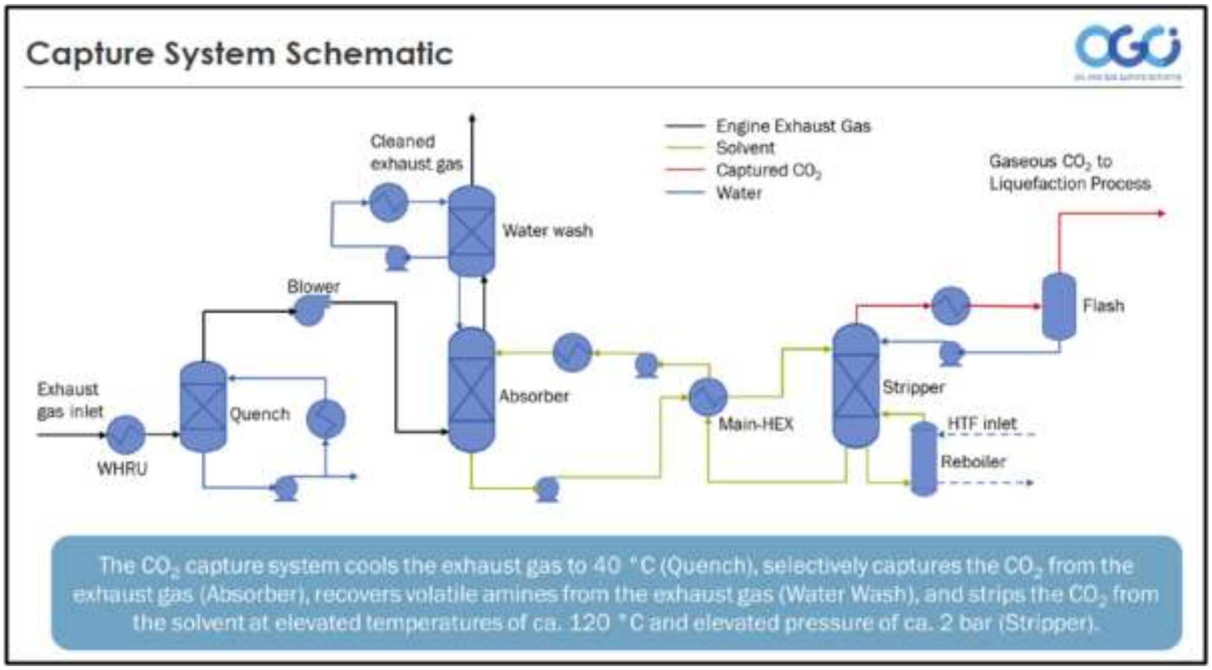
[6] StenaBulk. (2021, November). Is Carbon Capture on Ships Feasible? Oil And Gas Climate Initiative.
[7] Traver, M. (Ed.). (2023, March 22). An Update on Project ReMarCCAble. CMA Shipping Conference.
[8] Schmitt, T., Leptinsky, S., et al. (2022). Costs and Performance Baseline for Fossil Energy Plants - Volume 1: Bituminous Coal and Natural Gas to Electricity. DOE/NETL-2023/4320.
[9] SuezMax Tanker. (n.d.). [Image]. https://i.pinimg.com/. https://i.pinimg.com/originals/9e/f0/44/9ef04407227d859a7c124b6d2718f541.jpg

heated with heat introduced into the Reboiler. CO_2 is driven from the solvent and exits the top of the Stripper along with a significant amount of water vapor. CO_2 exiting the Stripper is cooled removing most of the water vapor and then flows to compression, drying, liquefaction, and storage. Lean solvent exiting the bottom of the Stripper flows to the Main-HEX and then is pumped to the top of the Absorber, thereby completing the solvent cycle.

Current research for solvent systems focuses on solvent development with efforts to reduce corrosivity, toxicity, and regeneration auxiliary requirements. The StenaBulk analysis is based on monoethanolamine (MEA) as the solvent. MEA is a mature solvent that was developed many decades ago. Discussion of other amines is included in the Technology Review Report.[2] StenaBulk indicates that 53% more fuel is required to provide auxiliary power for a 90% capture system that also captures CO_2 from the auxiliary power exhaust gas.[6] Based on this current study and reverse engineering, shaft power of 0.0213 kW/pph of CO_2 captured and thermal input of 1,500 Btu/lb_{CO_2} is required. In the NETL study, it is indicated that the CanSolv solvent only requires 1,050 Btu/lb_{CO_2}.[8] This TEA analysis uses the 1,050 Btu/lb_{CO_2} value which results in about 40% more fuel consumption instead of 53% more.


Capture System Schematic

The CO_2 capture system cools the exhaust gas to 40 °C (Quench), selectively captures the CO_2 from the exhaust gas (Absorber), recovers volatile amines from the exhaust gas (Water Wash), and strips the CO_2 from the solvent at elevated temperatures of ca. 120 °C and elevated pressure of ca. 2 bar (Stripper).

Figure 8 – Solvent Capture System Process Flow Diagram

3.2.4 Adsorbents

The RFI for a sorbent capture system was sent to InnoSepra (https://www.innosepra.com/). InnoSepra is very prominent in CO_2 capture from stationary power generation using solid sorbents. InnoSepra provided some technical information but not all the information requested in the RFI. Specifically, information that determines the auxiliary power requirements was provided. This includes thermal input of 1.5 MJ/MT_{CO_2} (645 Btu/lb_{CO_2}) and 2.0 psid to push exhaust gas through the capture system.

Additional power of 0.00939 kW-hr/lb$_{CO2}$ is required for vacuum pumps to regenerate the CO_2 adsorbent and deliver the CO_2 at atmospheric pressure.

Figure 9 shows a representative process flow diagram of the InnoSepra sorbent CO_2 capture process. A simplified description of the process is provided .[10] Exhaust gas from the ships engines, generator, and boiler will enter the capture system at stream 1 and be boosted in pressure. The major components of the system include the dehydration and SO_2 removal system (2 vessels on the upper left) and CO_2 removal system (3 vessels on the upper right). Exhaust gas enters stream 1 and flows first through the dehydration system from stream 14, to the CO_2 removal system through stream 21, and out of the CO_2 removal system through stream 23 to the second bed of the dehydration system where it is used to regenerate the dehydration sorbent. The exhaust gas cleaned of CO_2 and SO_2 exits the dehydration system through stream 5. CO_2 products are removed from the CO_2 Adsorbers through stream 29 and through the 2-stage vacuum pump system. From the surge tank, CO_2 will be introduced to the CO_2 compression and liquefaction system for the shipboard capture application. The balance of the system provides heating and cooling to assist in the regeneration of the dehydration and CO_2 removal sorbents.

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[10] Jain, R. (September 2015). Bench scale development and testing of a novel adsorption process for Post-Combustion CO_2 capture. https://doi.org/10.2172/1235558.

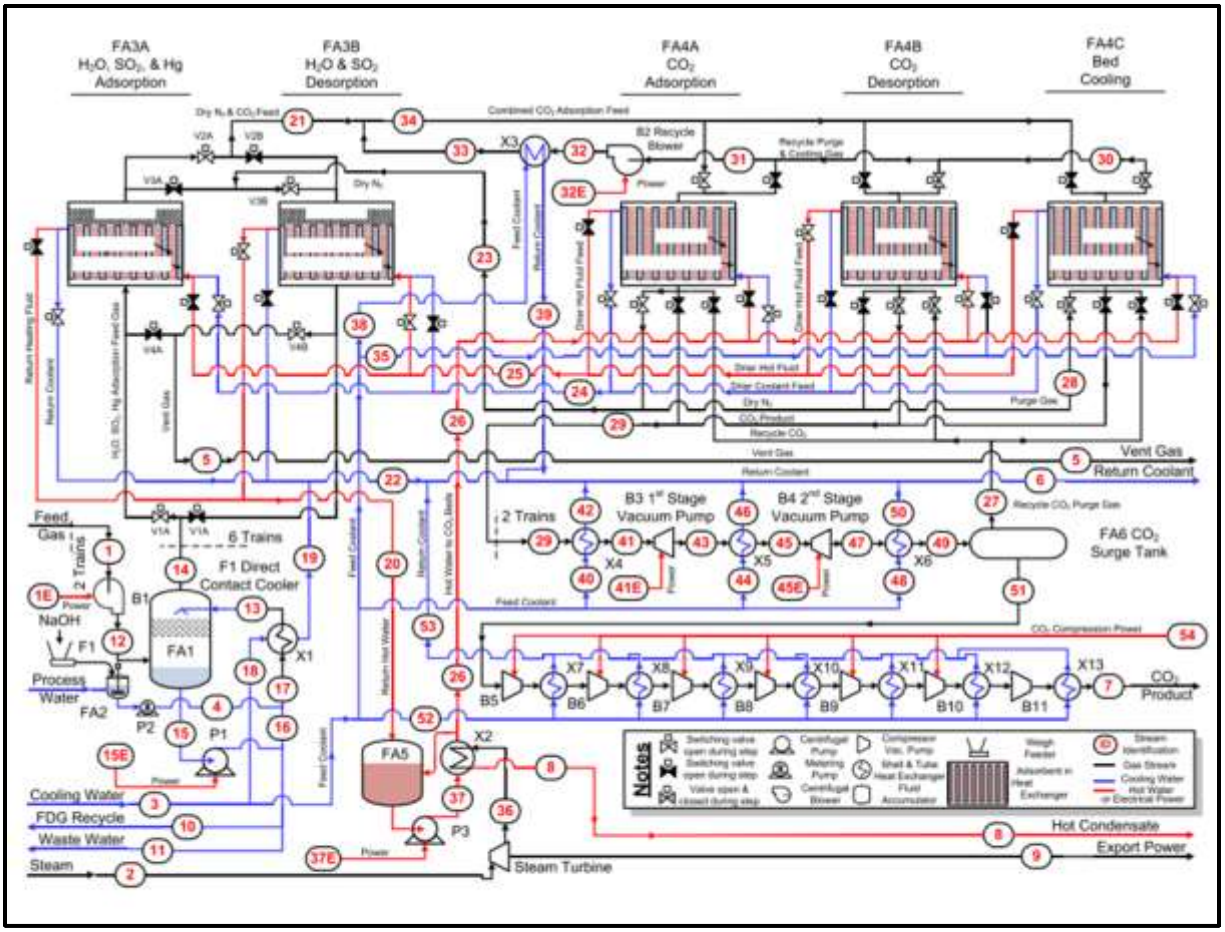

Figure 9 – InnoSepra Adsorbent Process Flow Diagram

3.2.5 Membranes

Information for a membrane system was requested from a membrane developer that is very prominent in CO_2 capture from stationary power generation. After a few communications regarding this application, it was concluded that a membrane is not a good technology because of the low CO_2 concentration in the exhaust gas (4 – 8%) and the high capture stipulation (90%). As a result of these communications, it was decided not to include a membrane case. Membrane separation is discussed in the Technology Review Report.[2]

3.3 CO_2 Compression, Liquefaction, and Storage

3.3.1 Compression and Liquefaction

Methods of onboard CO_2 storage were evaluated during the Technology Review phase of this study. During that work, it was concluded that the preferred way for onboard storage of the captured CO_2 (for all but the Calcium Looping process) is to pressurize, liquefy, purify, and store in a liquid phase in cooled pressure vessels at approximately -20°F (-28.9°C) and 300 psia (20.4 bar_a). Several studies for both onboard and land-based systems for pressurizing and liquefying CO_2 were reviewed to determine the preferred process flow sheet and auxiliary power requirements.[11,12,13] Two options are typically considered including external refrigeration and internal refrigeration. The external refrigeration option was selected for this TEA. A flow diagram of a 'typical' external refrigeration system is shown in Figure 10. The flowsheet in Figure 10 shows four stages of compression and a two-stage ammonia refrigeration system and follows the system optimized in the study by Deng, et al.[13]

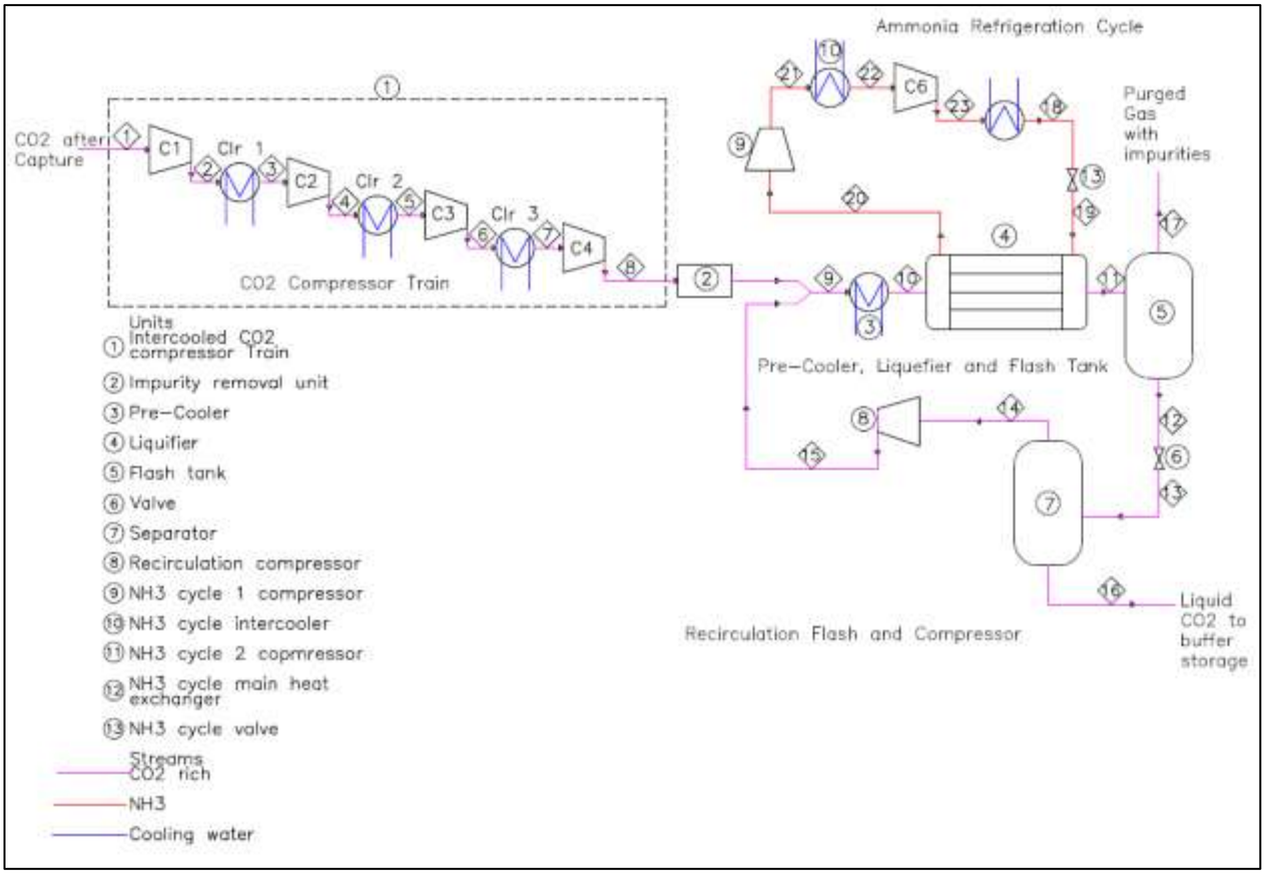

Figure 10 – CO_2 Compression and Liquefaction Process with External Refrigeration Type

CO_2 from the capture process is compressed and intercooled against cooling water in four stages with a nominal compression ratio of 2 in the Intercooled CO_2 Compressor Train (1). Water condensed in the intercoolers is removed as commonly done with air compression systems. The CO_2 is pressurized to the liquefaction pressure. For a storage pressure of 20 bar, the Deng study indicated a liquefaction pressure of 28 bar to be optimum. Special impurity removal (not considered in this study) could be performed in

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[11] Øi, L. E., Eldrup, N. H., Adhikari, U., Bentsen, M. H., Badalge, J. C. L., & Yang, S. (2016). Simulation and cost comparison of CO_2 liquefaction. Energy Procedia, 86, 500–510. https://doi.org/10.1016/j.egypro.2016.01.051.

[12] Speight, J. G. (2012). The chemistry and technology of coal. In CRC Press eBooks, 606-633. https://doi.org/10.1201/b12497.

[13] Deng, H., Roussanaly, S., & Skaugen, G. (2019). Techno-economic analyses of CO_2 liquefaction: Impact of product pressure and impurities. International Journal of Refrigeration, 103, 301–315. https://doi.org/10.1016/j.ijrefrig.2019.04.011.

(2). A water-cooled pre-cooler (3) is the compression system aftercooler and precools CO_2 before liquefaction. CO_2 is condensed in the liquefier (4). The liquefier is the evaporator in the two-stage ammonia refrigeration system (9-13). Any non-condensable components are separated from the liquid CO_2 in the flash tank (5). The removal of any impurities in the flash tank (5) will reduce the overall capture efficiency and increase the auxiliary power requirement as quantified in the Deng study. Liquid CO_2 is throttled through valve 6 to the storage pressure of 20 bar in the case of this study. CO_2 vapor that flashes across valve 6 is separated in the separator (7) and recycled back to the inlet of the liquefier.

From the Deng paper, the normalized auxiliary power for a system of pure CO_2 with 290 psia (20 bar_a) storage pressure, 410 psia (28.3 bar_a) liquefaction pressure, and 50°F (10°C) cooling water is 90 kW-hr/$tonne_{CO2}$. **For this study, 68°F (20°C) cooling water temperature will be used which increases the normalized auxiliary power to approximately 100 kW-hr/$tonne_{CO2}$.**

3.3.2 Storage

Cryogenic storage is the most common way of storing captured CO_2. For this study, 50-ton nominal capacity bulk storage tanks were selected. The 50-ton tanks are almost 40 feet long and 10 feet in diameter. This is roughly the maximum size object that can be readily transported by road or rail. The Map Runner requires 2 tanks to hold the CO_2 captured during a 7 day period. The Seaways Brazos requires 52 to 55 tanks to hold the captured CO_2 during a 21-day period.

Storage of high-pressure CO_2 (3000 psi), solid CO_2 (dry ice) and other methods such as metal hydride storage were investigated but are not as economical as liquid storage.

3.4 Fresh and spent sorbent storage and handling

Another method of storing captured CO_2 is to use calcium oxide (CaO) and react it with the CO_2 in the exhaust gas stream. This produces calcium carbonate ($CaCO_3$). The system proposed by Seabound is described above. The pellets are approximately 0.4 inches in diameter, and 0.4 inches long. Both types of pellets are relatively awkward to convey. Pneumatic conveyor systems appear to be the best technology available to handle these pellets. The CaO and $CaCO_3$ pellets are stored in bins. The bin size chosen has a capacity of 50 to 55 tons, although other bin sizes are certainly possible.

A recent advancement involves an alternative, modularized sorbent storage system that eliminates the need for solids conveying. For further details, refer to APPENDIX B.

A minor complexity for some installations will be the prevention of progressive flooding. Progressive flooding can be prevented by installing valves or by installing piping so that progressive flooding cannot occur.

3.5 Auxiliary Power for CO_2 Capture and Compression Systems

3.5.1 Electricity

Additional electrical power will be required for all CO_2 capture and storage technologies evaluated. The Map Runner requires between approximately 100 and 300 kW for all the technologies except calcium looping, which will require approximately 70 kW. The Seaways Brazos requires between approximately

4000 and 7000 kW for all of the technologies except calcium looping, which will require approximately 1,000 kW. Significant electrical power generation additions are required for all technologies except the calcium looping. Electrical power requirements for the calcium looping are significantly lower than the other technologies, but will still almost certainly require an additional electrical generator for each vessel. Calcium looping produces high temperature waste heat which may be harvested to offset the electrical power consumption. The waste heat recovery process is not modeled in this study.

3.5.2 Thermal Energy

Additional thermal energy is required for the solvent based CO_2 capture technology. The Map Runner requires approximately 32 kW in addition to the exhaust gas energy, and the Seaways Brazos requires approximately 1000 kW in addition to the exhaust gas energy. This can either be provided by electric heaters or a boiler. In both cases, a boiler was selected to provide additional energy for the process. The cryogenic process requires a small energy input for the Seaways Brazos. It is likely that an existing boiler system can provide that amount of energy without requiring additional equipment.

4 Economic Analysis

4.1 Modeling Parameter

Many assumptions are required to perform a TEA. Depending on the specific application, there can be different assumptions made. To make this analysis as transparent as possible, a list of the modeling parameters is included in Table 1. The Modeling Parameters are loosely divided into categories of:

- Process Parameters
- Economic Parameters
- Equipment Costs
- Operating Costs

It is noted that detailed layout of any of these systems is beyond the scope of this study. It is noted that all technologies will have challenges regarding space and weight requirements. While the two vessels operate on different fuels with different heating values and fuels costs, a single value for each parameter was chosen so that any differences would be based on the technology or ship selection and not the fuel.

Table 1 – Modeling Parameters

Analysis Parameters		
Process Parameters		
Blower Efficiency	65%	
Auxiliary Generator Efficiency, fraction of fuel heating value	40%	
Oil-fired boiler Efficiency, fraction of fuel heating value	90%	
CO_2 Comp. and Liquefaction Power, kW/(tonne/hr)	100	
CO_2 Comp. and Liquefaction Cooling Requirements, kW/(tonne/hr)	206	
Cooling Water temperature Range, °F	10	
Pressure of Stored Liquid CO_2, psig	200	
Temperature of Stored Liquid CO_2, °F	**-20.1**	
Density of Liquid CO_2, lb/ft^3	**66.9**	
Fresh sorbent (calcium looping) bulk density, $tonne/m^3$	1.10	
Fresh sorbent (calcium looping) bulk density, lb/ft^3	**68.7**	
Spent sorbent (calcium looping) bulk density, $tonne/m^3$	1.80	
Spent sorbent (calcium looping) bulk density, lb/ft^3	**112.4**	
Economic Parameters		
Capital Cost Scaling Exponent	0.7	
Project Term, yr	20	
Value of Money	7.00%	
Capital Charge Factor (CCF)	**0.094**	
	Map Runner	Seaways
Fuel cost, \$/MMBtu	10	10
Fuel Heating Value, Btu/lb	20,495	20,495
Trip Time, days	7	21
Capacity Factor, %	50%	50%
Equipment Costs		
Refrigeration/compression plant, \$/(ton/hr CO_2)	\$250,000	
Auxiliary Generator	Output, kW	Cost
	150	200,000
	2,000	1,700,000
Auxiliary Generator, Cost = MX^b	M, \$/kW	3,185
	b	0.8262
	CO_2	Sorbent
Storage Tank Capacity, tonnes CO_2 or Spent Sorbent	50	**51**
Storage Tank Capacity, ft^3	**1,648**	1,000
Storage Tank Estimate	\$250,000	**\$27,898**
Storage Tank Weight, lb	55,000.00	**6,138**
Storage Tank Cost, \$/lb	**\$4.55**	**\$4.55**
Operating Costs		
Annual Equipment Maintenance Cost, % of initial cost	2.0%	
CaO cost, \$/tonne	\$63.00	

4.2 Utility Requirements

The quantity of electrical power and thermal power required to operate the capture, compression, and liquefaction systems is required for this analysis and is calculated for the respective technologies as described below. For the case of the cryogenic capture system and the calcium looping system, the technology developers provided actual values for specific sized capture systems. These values were normalized (determined as a function of CO_2 capture rate) so they could be used as the capture system size changes resulting from additional exhaust gas from auxiliary power generation. The calcium looping system generates high quality waste heat which can potentially be recovered to reduce utility requirements, but that is beyond the scope of this study. For the solvent technology, a thermal requirement of 1,050 Btu/lb_{CO2} is used and an electrical power requirement of 0.0213 $kW\text{-}hr/lb_{CO2}$ obtained from an NETL report for CanSolv solvent.[8] For the sorbent system, thermal requirement of 645 Btu/lb_{CO2} and electrical power requirement for vacuum pumps of 0.00939 $kW\text{-}hr/lb_{CO2}$ were provided from reports published by the technology developer.

Auxiliary power for the exhaust gas booster fan is calculated from fan law equations and pressure drop provided by the technology developers. For the CO_2 Compression and Liquefaction system, an auxiliary power requirement of 100 $kW\text{-}hr/tonne_{CO2}$ is used for all technologies based on the study by Deng .[13]

Using the above information in spreadsheet calculations, auxiliary power requirements are calculated and shown in Figure 17 and Figure 18. Realizing that most if not all of the thermal energy requirement is provided from the exhaust gas, the additional fuel consumption required is calculated and shown in Figure 11 and Figure 12.

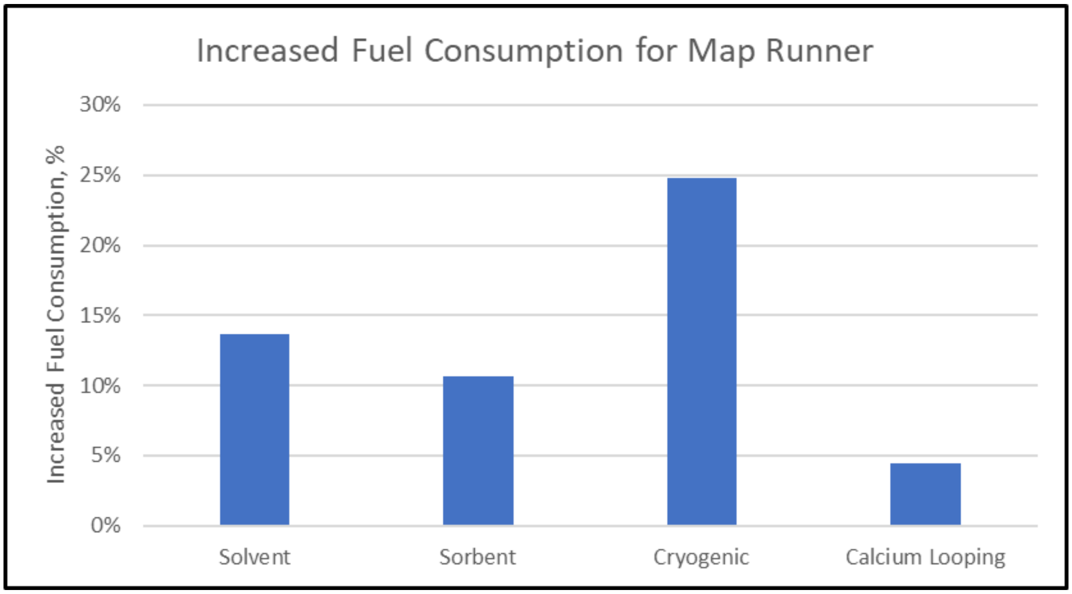

Figure 11 – Increased Fuel Consumption for Map Runner

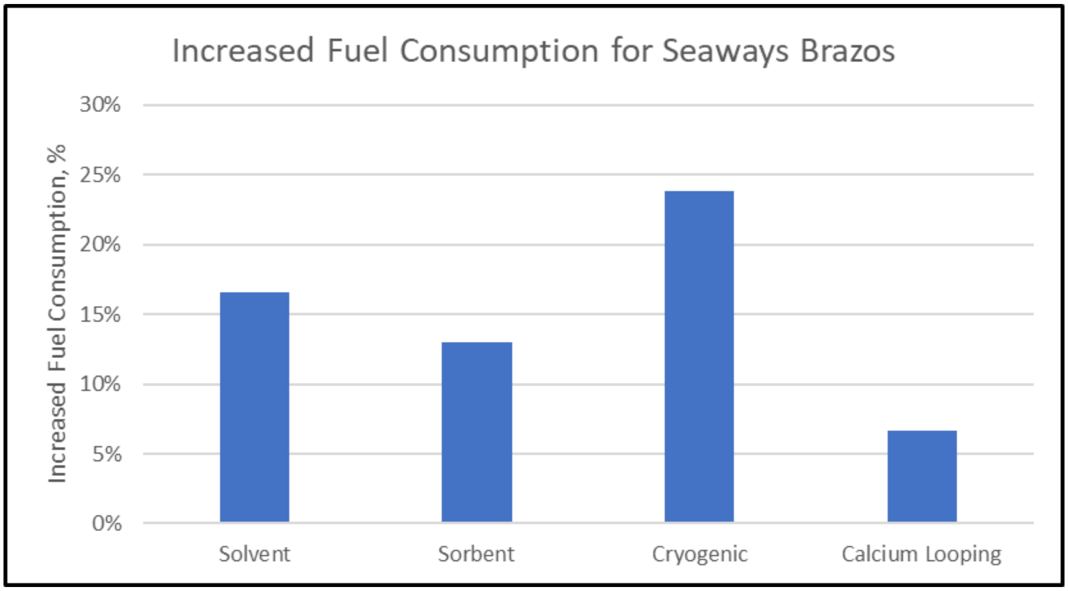

Figure 12 – Increased Fuel Consumption for Seaways Brazos

4.3 Capital Cost Estimation

For this study, the capital cost was divided into the Capture System, Compression and Liquefaction (Solids Transport for Calcium Looping) System, Storage, and Miscellaneous Capital cost. *Installed capital cost* is estimated by multiplying the *equipment cost* by a *Lang factor,* assumed in this study to be 1.6. Utilizing a Lang Factor is a common approach to estimate installed cost for technologies that are being developed or for preparation of budget estimates. The equipment costs for the capture systems were obtained directly from technology developers or publications authored by technology developers. Since the Compression and Liquefaction, Storage, and Miscellaneous Equipment are more conventional, estimates for these were requested/obtained from vendors or the internet, etc. so there was consistency between technologies. There was no effort to obtain multiple bids or foreign pricing to obtain the least cost option. Competitive bidding is beyond the scope of this study. Competitive bidding would be done if a Front-End Engineering and Design (FEED) were done for any of these technologies.

Equipment cost scaling for capacity was performed using the conventional equation:

$$Cost = Cost_{ref} x \left(\frac{Capacity}{Capacity_{ref}}\right)^{n}$$

Where:

- Capacity – process capacity of interest, e.g. this could be the CO_2 capture rate or exhaust gas flow rate
- $\text{Capacity}_{\text{ref}}$ – process capacity at reference conditions
- Cost – Equipment cost at the new capacity
- Cost_{ref} – Equipment cost at the reference capacity
- n – scaling exponent (value of 0.7 was used)

As the system design was iterated to provide auxiliary power requirements, the component sizes are changed as more or less exhaust gas is produced. Consequently, the above scaling factor was applied to all the capital costs, even those provided by the technology suppliers for their systems sized to treat the baseline exhaust gas from the ship. The capture system cost will increase as the exhaust gas and CO_2 capture rate increase due to the need to provide auxiliary power.

4.3.1 Capture Systems

Developers were asked to provide capital cost estimates for the hardware for their systems. Capital cost estimates were provided by PMW for the cryogenic technology and Seabound for the Calcium Looping. For the solvent and sorbent technologies, capital costs are obtained from technical papers and reports and scaled using the above scaling equation for the size required for this study.

4.3.2 Compression and Liquefaction System

Several vendors were asked to provide estimates for the compression/liquefaction portion of this TEA. No vendor responded with cost information. Therefore, the cost estimate was based on the author's research on commercial and marine compressors and refrigeration equipment. For the Map Runner, the compressors are estimated to cost approximately \$50,000 and the refrigeration equipment is estimated to cost approximately \$150,000. For the Seaways Brazos, the compressors are estimated to cost approximately \$250,000 and the refrigeration equipment is estimated to cost approximately \$1,350,000.

4.3.3 CO_2 Storage System

Most of the CO_2 capture methods produce gas. Providing reasonably dense storage without excessive compression or cooling is required. Liquid CO_2 storage at approximately 300 psi and -20 degrees F is a relatively economical method. Different sized tanks were considered, and a 50 ton nominal capacity tank was selected for this study based on cost, availability, and transportability. Cyl-Tec was contacted, and they provided a cost estimate of approximately $250,000 per tank, not counting any piping, valving, or installation costs. The cost of piping, valving, and a chiller plant to keep the tanks cold is $450,000 for the Map Runner, and just over $6,000,000 for the Seaways Brazos. This $6,000,000 is captured in the lang factor applied to the storage tanks.

The calcium looping solids handling system requires air compressors and associated piping for a system to handle the Map Runner, the installed air compressor cost will run $40,000 to $60,000. For a system to handle the Seaways Brazos, the installed air compressor cost will run $80,000 to $150,000. The piping for the conveyors will depend on the tank layout. Costs for the conveyor piping and valving are in the range of $40,000 for the Map Runner and $200,000 for the Seaways Brazos. Installation costs will be in the range of $100,000 for the Map Runner and $500,000 for the Seaways Brazos.

4.3.4 Sorbent (Fresh and Spent) Storage Bins

The capacity and shape of sorbent storage bins would be selected for suitable placement in any ship of interest during a detailed design. For the purpose of this TEA, for costing and estimating weight, it was assumed that the bins would be 10 feet by 10 feet by 10 feet fabricated from ¼” thick carbon steel plate. As shown in Table 1, this yields a weight of 6,138 lb and a cost of $27,880 per bin (assumes $4.55/lb including material and fabrication). A bin can hold ~51 tonnes of spent sorbent.

4.3.5 Miscellaneous Capital Costs

Miscellaneous capital equipment include exhaust gas booster blower, exhaust gas cooler, and auxiliary power generator.

4.3.5.1 Exhaust Gas Booster Blower

The exhaust gas booster blower motor size is calculated using the equation:[14]

$$P = 0.746\ x\ (Q\ x\ head)/(229\ x\ \mu)$$

Where:

- *Head* – Blower head (psid)
- *P* – power (kW)
- *Q* – flow rate (acfm)
- μ - blower efficiency (65% as shown in Table 1)

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[14] Engineers Edge LLC (n.d.). *Fans and blower horsepower equation*. https://www.engineersedge.com/motors/fans_blower_horsepower_equation.htm.

After the blower power is determined, the capital cost is estimated by multiplying the blower power consumption by \$500, i.e. \$500/kW.

4.3.5.2 Exhaust Gas Cooler

The purpose of the exhaust gas cooler is to recover thermal energy from the exhaust gas to use as required in the capture system and lower the flue exhaust gas temperature to ~100°F for the solvent, sorbent, and cryogenic capture systems. The calcium looping capture system operates at elevated temperature so there is no need to cool exhaust gas for that capture system. It is assumed that the availability of exhaust gas thermal energy is limited to 250°F. Thermal energy below this temperature will be rejected to cooling water.

An overall heat transfer coefficient of 25 Btu/hr-ft^2-°F is assumed, and the required heat exchange surface is calculated based on the heat duty and log mean temperature difference. A water temperature of 100°F is assumed. Based on an internet search, a capital cost estimate based on \$100/ft^2 is assumed for the exhaust gas cooler.

4.3.5.3 Auxiliary Power Generator

Auxiliary power requirements are a sum of exhaust gas booster blower, capture system, and compression and liquefaction. The total auxiliary power for each capture system is determined and the capital cost of the generator is determined to provide this output. Capital costs for the auxiliary generator are determined from the equation in Table 1.

4.4 Operating and Maintenance Cost

4.4.1 Auxiliary Power Fuel Cost

The total auxiliary power requirement is the sum of the exhaust gas booster blower, capture system, and compression and liquefaction system. This total auxiliary power along with an assumed generator efficiency of 40% is used to calculate the additional fuel for auxiliary power. The additional fuel cost for auxiliary power is calculated using the increased fuel consumptions given in Figure 11 and Figure 12 and multiplying by the ships baseline fuel flow rate. Fuel costs (\$/MMBtu) and fuel heating value (MMBtu/lb) are given in Table 1.

4.4.2 Consumables

All the capture technologies evaluated require consumable materials. The solvent system requires solvent makeup as some solvent degrades because of exposure to SO_2 and NOx. The sorbent system will require sorbent replacement every three to five years. The cryogenic system will require the replacement of some zirconia beads used in the moving bed heat exchangers. The fresh sorbent for the calcium looping process is a consumable and as seen in Figure 15, Figure 16, Figure 19, and Figure 20 represents the majority of the Cost of CO_2 Captured and Avoided for this technology. While consumable costs are included for all the technologies, they are insignificant in all but the calcium looping technology.

4.4.3 Equipment Maintenance Cost

Annual equipment maintenance cost is assumed to be 2% of the initial capital cost of the equipment.

4.4.4 Lost Shipping Revenue

Lost shipping revenue will be directly impacted by the weight of the equipment, volume of the equipment, and the stored CO_2 or sorbent material. Unfortunately, the revenue model is different for each of the types of vessels that were modeled in this study. To keep it simple, the following is the approach used in this study to estimate lost shipping revenue. This report has been reviewed with the shipping companies and their revenue impact comments are included in APPENDIX B.

The weight of the equipment and capture CO_2 or sorbent is shown in Figure 13 and Figure 14 as a percentage of the ship's deadweight capacity. A simple calculation is performed to estimate lost revenue resulting from the reduction in deadweight capacity. The equation used is:

$$LSR = Red.\,Deadweigh\ Capacity\ x\ Base\ Fuel\ Flow\ Rate\ x\ Fuel\ Cost$$

$$x\ Fuel\ Heating\ Value\ x\ \frac{8760\ hours}{year}\ x\ Capacity\ Factor\ x\ Multiplier$$

Where:

- *Base Fuel Flow Rate* – Fuel flow rate at what is determined to be the normal operating ship speed (pph)
- *Capacity Factor* – A capacity factor of 50% is assumed for this analysis
- *Fuel Cost* – Cost of bulk fuel ($/MMBtu) – Values used are listed in Table 1
- *Fuel Heating Value* – Fuel Heating Value (Btu/lb) – Values used are listed in Table 1
- *LSR* – Lost shipping revenue ($/yr)
- *Red. Deadweight Capacity* – Reduction in deadweight capacity (%) – these values are provided in Figure 13 and Figure 14
- *Multiplier* – Lost Revenue divided by fuel cost required to overcome capture and storage weight – a value of 3 is used in this study

4.5 Omitted Items

Items not considered in this study include:

- Lost revenue due to downtime for installation and construction of the capture and storage system
- Incremental shipboard labor cost to operate the capture and storage system
- Offloading of the captured CO_2 or fresh and spent sorbent
- Taxes
- CO_2 capture credits

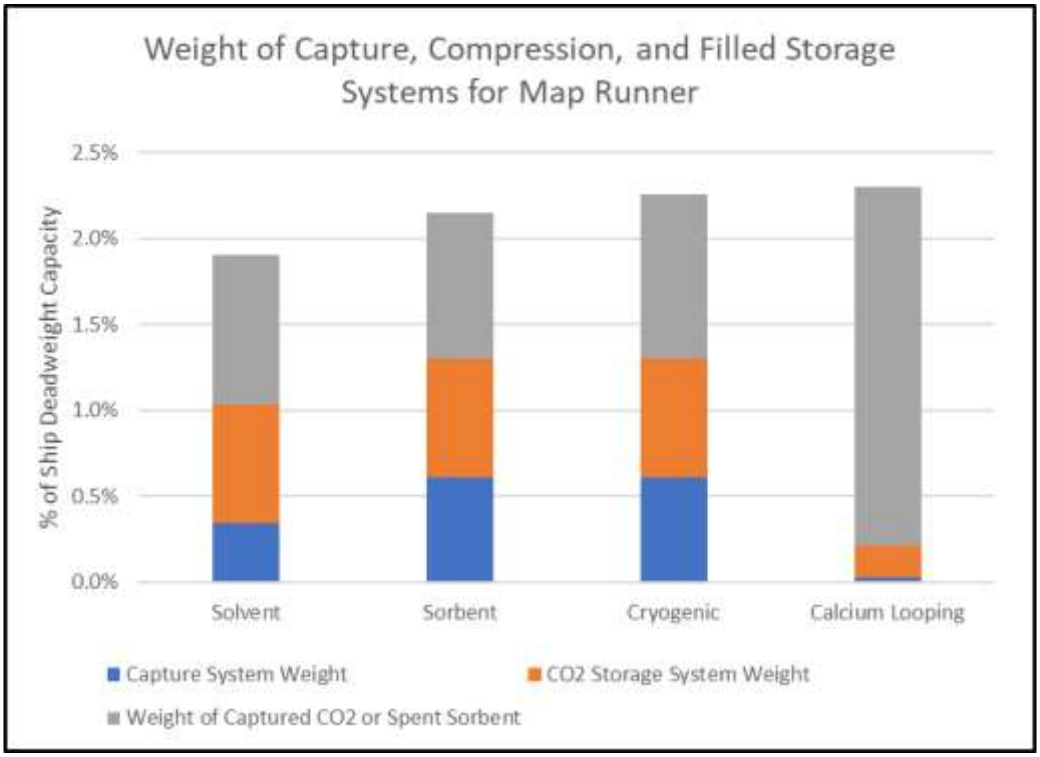

Figure 13 – Weight of Capture, Compression, and Filled Storage systems for Map Runner

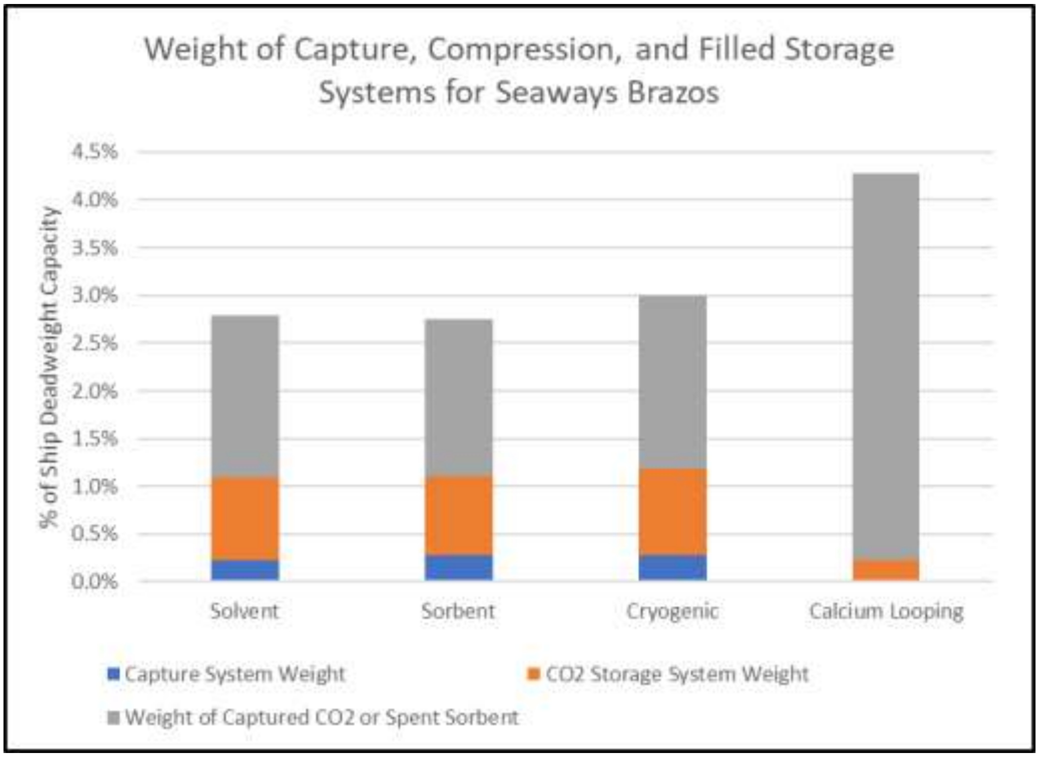

Figure 14 – Weight of Capture, Compression, and Filled Storage Systems for Seaways Brazos

4.6 Cost of CO_2 Captured and Avoided

The Cost of CO_2 Captured is determined using the equation below.

$$Cost\ CO2\ Captured = \frac{(CCF\ x\ Capital\ Cost + Operating\ and\ Maintenance\ Cost)}{CO2\ Captured}$$

Where:

- *CCF (Capital Charge Factor)* – this is basically the amortization rate for the capital equipment (Interest rate and term assumed for this project are given in Table 1) – CCF = 0.094
- *Capital Cost* – Capital Cost is the sum of the equipment cost discussed above (Capture System, Compression and Liquefaction, Storage, Booster Blower, Exhaust Gas Cooler, and Auxiliary Generator)
- *Operating and Maintenance Cost* – Operating and Maintenance Cost is the sum of the items discussed above in 4.4
- *CO_2 Captured* – This is the quantity of CO_2 Captured in one year as shown in Figure 19 and Figure 20

The Cost of CO_2 Avoided is calculated in a similar manner as the Cost of CO_2 Captured except the denominator is CO_2 Avoided.

$$Cost\ CO2\ Avoided = \frac{(CCF\ x\ Capital\ Cost + Operating\ and\ Maintenance\ Cost)}{CO2\ Avoided}$$

Where:

- *CO_2 Avoided* – This is the quantity of CO_2 Avoided in one year as shown in Figure 19 and Figure 20

4.6.1 Cost of CO_2 Captured

Figure 15 and Figure 16 show the results of the study providing the estimated Cost of CO_2 Captured for the Map Runner and Seaways Brazos, respectively. The Cost of CO_2 Captured ranges from about \$150 – 220/tonne CO_2 for both ships and all capture technologies. Variations between technologies are within the range of accuracy of the study. As seen in the legend of these charts, the cost is broken into four capital cost elements, three O&M cost elements, and one lost revenue element.

Comparing costs between the Map Runner and Seaways Brazos, economies of scale would be expected to reduce the cost for the Seaways Brazos. While this is true and relatively small for all but the calcium looping, there are a couple important factors that diminish the economies of scale. The trip time (time between CO_2 unloading) for the Map Runner is assumed to be 7 days but for the Seaways Brazos it is assumed to be 21 days. Consequently, the relative capital cost for the CO_2 storage system is larger for the Seaways Brazos than for the Map Runner. Modeling Parameters including the trip times are tabulated in Table 1.

Additionally, the exhaust gas temperature for the Seaways Brazos is less than for the Map Runner resulting in relatively less heat available from the exhaust gas to power (thermal energy only) the capture system. Auxiliary power requirements are shown in Figure 17 and Figure 18. The Auxiliary Electric shaft power is provided by added generators. Thermal power, to the extent available, is absorbed from the exhaust gas. The solvent system requires the maximum amount of thermal energy, and it is not all available from the exhaust gas so it must be supplemented with an auxiliary boiler as shown by the gray bars.

Finally, the cost of capture for the Calcium Looping technology is dominated by the Consumable element. For the Calcium Looping technology, $Ca(OH)_2$ (Map Runner) and CaO (Seaways Brazos) are the fresh sorbent material that capture the CO_2. The spent sorbent is $CaCO_3$ which is stable and stored in pellet form. Processing of the spent sorbent is done on shore. The cost of the onshore processing is captured in the Consumables cost.

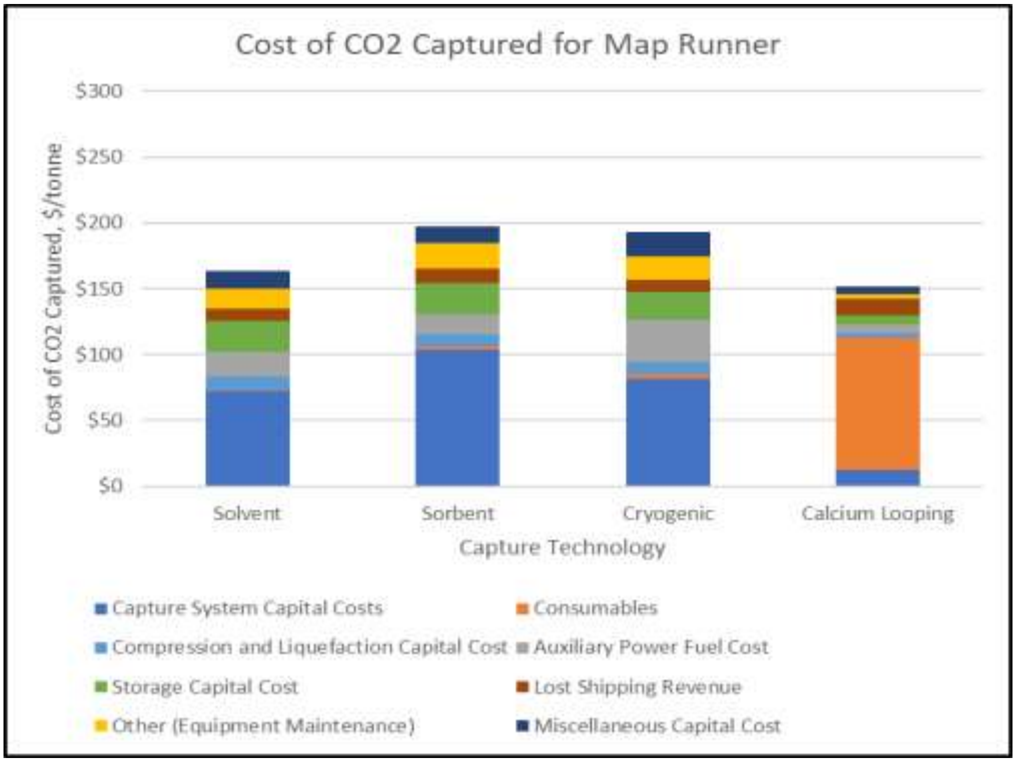

Figure 15 – Cost of CO_2 Captured for Map Runner

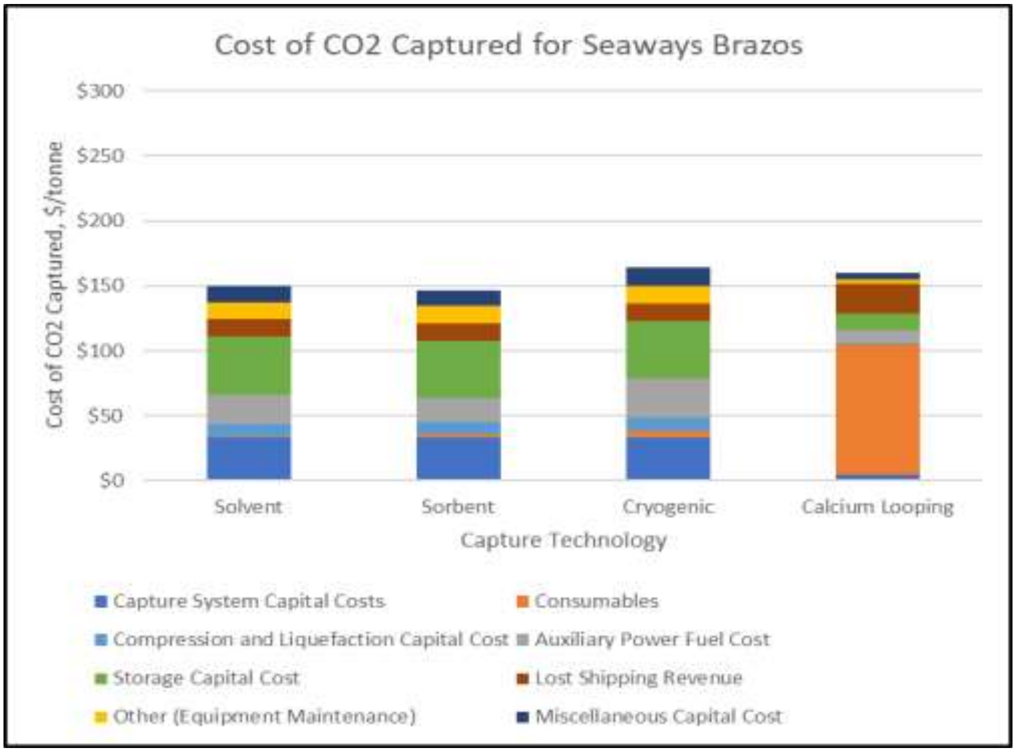

Figure 16 – Cost of CO_2 Captured for Seaways Brazos

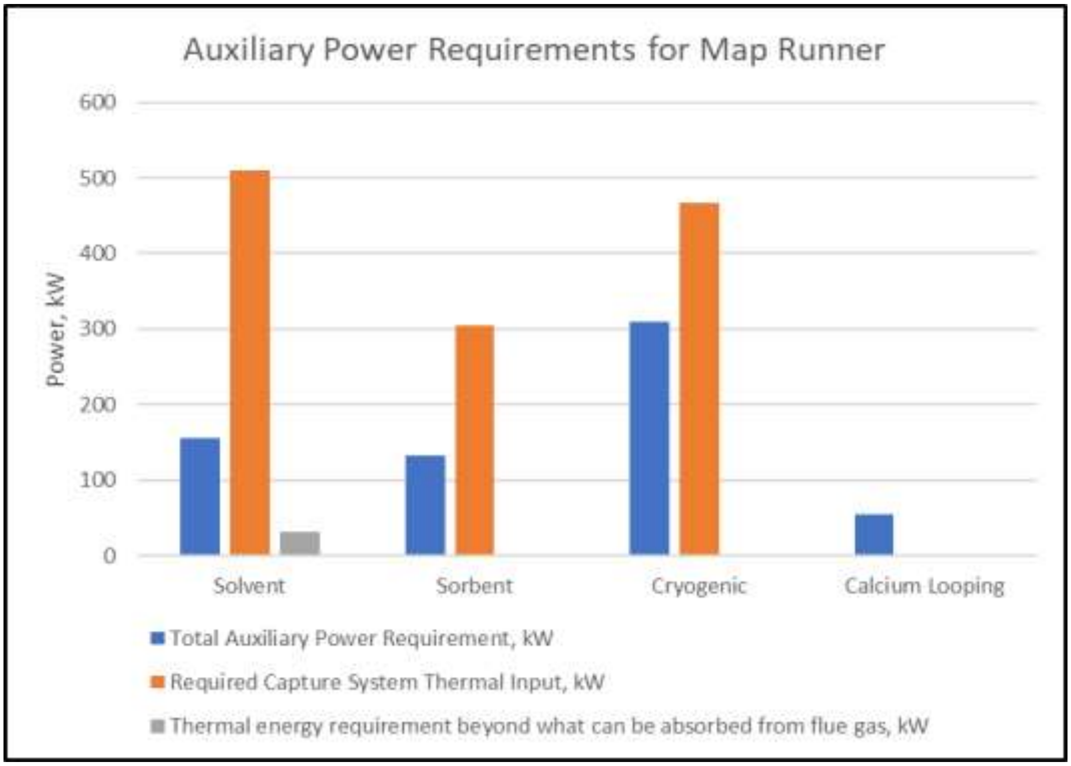

Figure 17 – Auxiliary Power Requirements for Map Runner

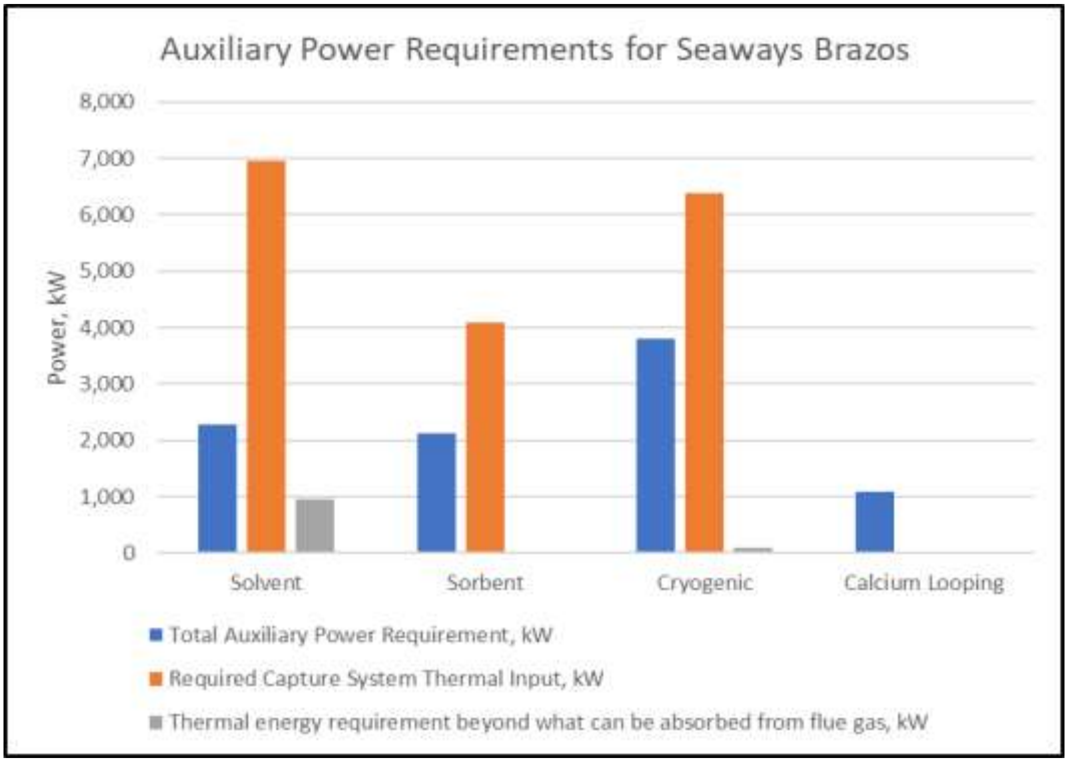

Figure 18 – Auxiliary Power Requirements for Seaways Brazos

4.6.2 Cost of CO_2 Avoided

A second and arguably more important Figure of Merit is the Cost of CO_2 Avoided. The Cost of CO_2 Avoided considers operating costs and the cost of CO_2 emissions. Therefore, Costs of CO_2 Avoided will always be greater than the Costs of CO_2 Captured unless no auxiliary fuel is required to operate the capture system. As shown in Figure 21 and Figure 22, the Quantity of CO_2 Avoided for all cases is less than the Quantity of CO_2 Captured. This is because additional fuel beyond the ship's propulsion and service requirements is used to provide the auxiliary heat and/or power to operate the capture and storage system. The capture technologies requiring the greatest amount of auxiliary power will have the largest difference between CO_2 Captured and CO_2 Avoided. CO_2 from exhaust gas generated by the auxiliary power systems is also treated further increasing the quantity of auxiliary power required. All of this is included in this analysis.

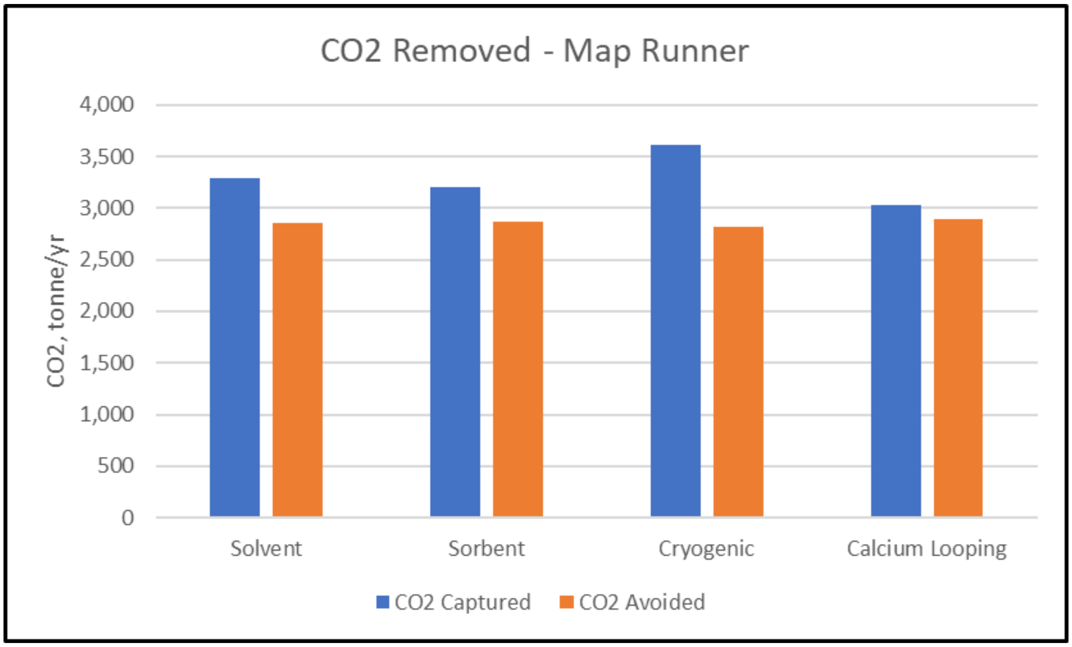

Figure 19 – CO_2 Removed for Map Runner

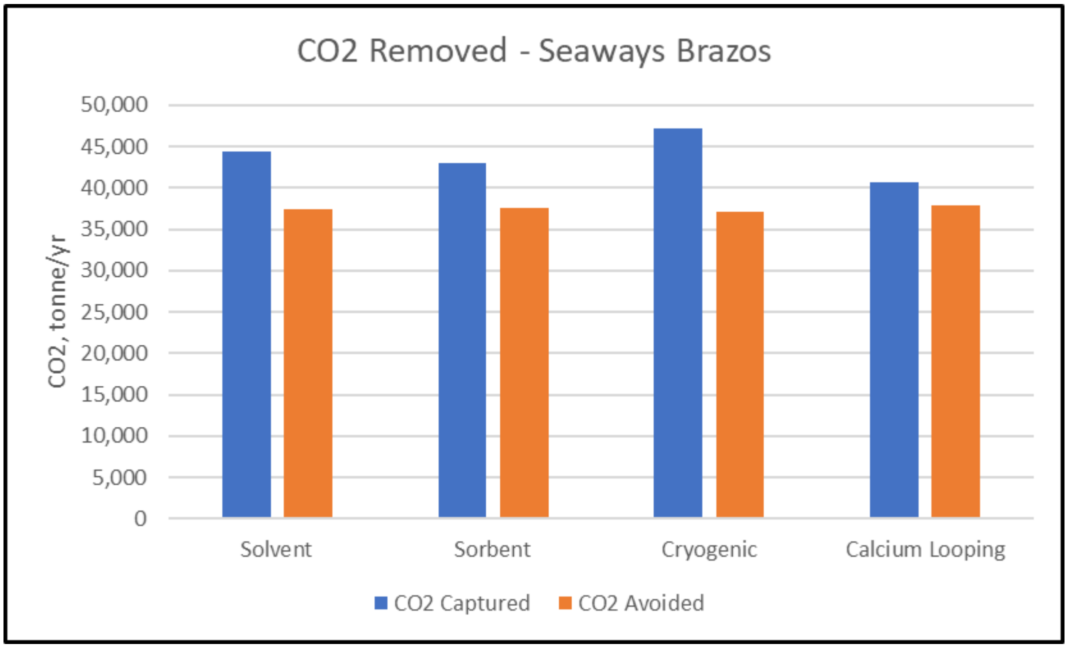

Figure 20 – CO_2 Removed for Seaways Brazos

Costs of CO_2 Avoided are shown in Figure 21 and Figure 22. The Cost of CO_2 Avoided is greater than the Cost of CO_2 Captured. The capital and O&M costs are unchanged but the denominator in the Cost of CO_2 Avoided is less as shown in Figure 19 and Figure 20.

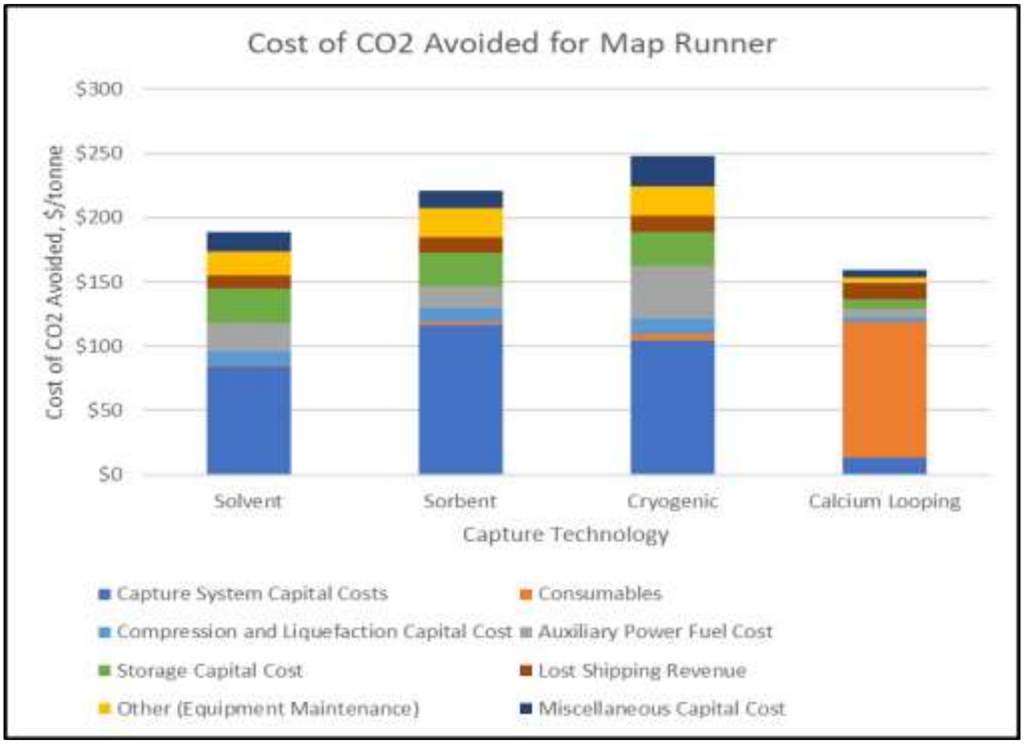

Figure 21 – Cost of CO_2 Avoided for Map Runner

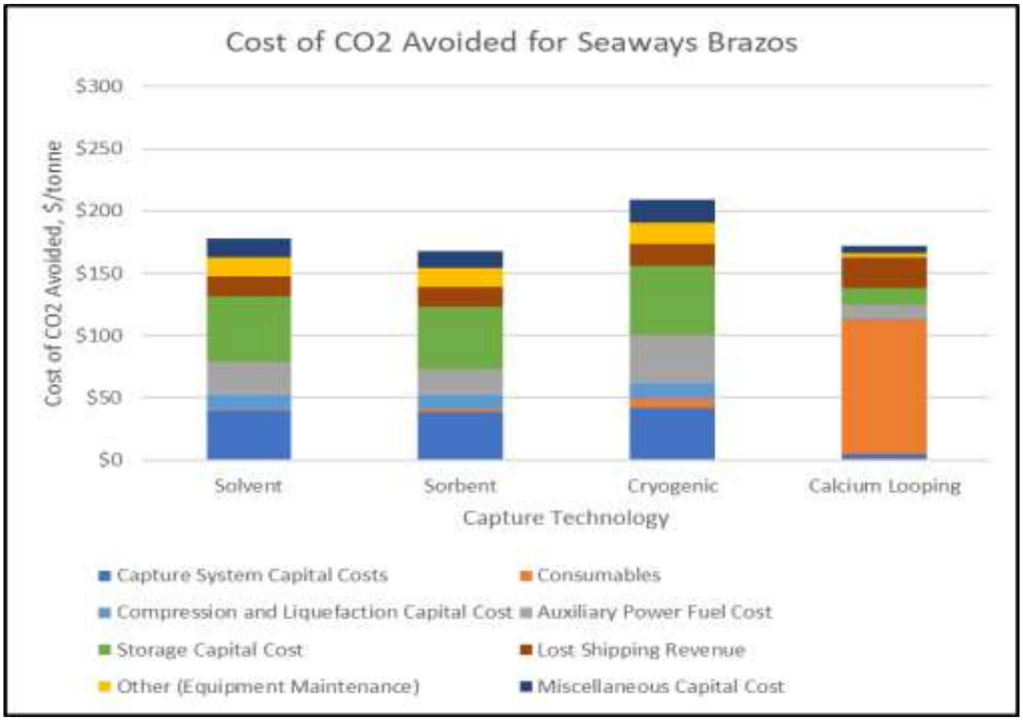

Figure 22 – Cost of CO_2 Avoided for Seaways Brazos

5 Summary/Conclusions

Based on this techno-economic analysis, it is estimated that shipboard CO_2 capture and storage can be performed for a cost ranging from approximately $150 to 200/tonne CO_2 captured depending on the ship and the capture technology. The Cost of CO_2 avoided is higher, ranging from approximately $175 to $250/tonne CO_2 avoided depending on the technology selected. These estimates are believed to be accurate to within about 30% for the assumed modeling parameters.

It is noted that many assumptions are required in the form of modelling parameters that can have a significant impact on the economic analysis. Most of these parameters are listed in Table 1. The importance of a few of these parameters will be discussed here.

Trip times of 7 days for the Map Runner and 21 days for the Seaways Brazos were assumed. In a similar manner, the ship capacity factor (fraction of output divided by maximum output of the ship) will have a big impact on the:

- Quantity of CO_2 that must be stored on board and shipped to the final destination
- Capital cost of the storage system
- Additional fuel that must be available and hauled along the route

The Capital Charge Factor (CCF) is the annual payment for the capital equipment. This is a function of the assumed value of money and the life of the equipment (term of the financing). For this study, a value of money of 7% and term of 20 years was assumed. This is a very simple economic analysis that results in a CCF of 0.094.

Several items not included in this analysis are listed in section 4.5. There will inevitably be financial incentives for shipping companies to deploy decarbonization technologies of which carbon capture is one. The details of these incentives are certain to be complex and beyond the scope of this TEA.

A few highlights of the analysis results worth noting:

- The economics of the Calcium Looping Technology is dominated by the cost of the consumable (fresh sorbent) as seen in the Cost of CO_2 Captured and Avoided charts, Figure 15, Figure 16, Figure 21, and Figure 22. The cost of the fresh sorbent will depend on the onshore regeneration of the spent sorbent. A value of $63/tonne for fresh sorbent was provided by the technology supplier. Provided by the technology developer, "*The $63/tonne figure includes the cost of zero/ultra-low-emissions calcination process, factoring in the assumption that spent sorbent undergoes recycling with a 10% purge rate for the regeneration of fresh sorbent and pure CO_2. To align with the scope of this study and ensure a fair comparison with other technologies, downstream CO_2 transportation as well as sequestration costs were not included." Treating regeneration of the sorbent in this manner puts the technologies on an equal basis since unloading and sequestration of the captured CO_2 is not included for any of the technologies.*
- Economies of scale that would typically be expected comparing the Seaways Brazos to the Map Runner are largely erased because of the longer trip time and higher percentage cost for the CO_2 storage. Note comparing Figure 15 to Figure 16, the percentage of the capture cost attributed

to Storage capital cost is greater for the Seaways Brazos. Capital cost for the capture system is proportionately less for the Seaways Brazos.

- The weight of the capture, compression, and filled storage systems as shown in Figure 13 and Figure 14, is dominated by the stored CO_2 or spent sorbent, followed by the storage tanks or bins. The weight of the capture system is irrelevant for the Seaways Brazos and relatively small for the Map Runner.
- Auxiliary Power Fuel Cost is the third largest element in the Cost of CO_2 Captured and Avoided behind Capture System Capital Cost and Storage System Capital Cost for the solvent, sorbent, and cryogenic systems as shown visually in Figure 15, Figure 16, Figure 21, and Figure 22.
- For the sorbent and cryogenic capture systems, the required thermal energy for regeneration is available from the exhaust gas thermal energy as shown in Figure 17 and Figure 18. The solvent system requires the most thermal energy and a high percentage of this is available from the exhaust gas.
- The only auxiliary energy required for the Calcium Looping Technology is electric power for the exhaust gas booster blower. This power is proportionally larger than for the other technologies because the exhaust gas must be boosted while it is at an elevated temperature.

Much attention has been given to demonstrating the solvent technology due to its level of maturity. The three other technologies studied here have technical and economic merit based on this study and it is recommended that they should be given serious consideration for demonstration as well. Based on information provided by the cryogenic and calcium looping technology providers, they are in the process of performing prototype tests. The sorbent technology developer is focusing exclusively on stationary power. Based on this study, it appears the sorbent technology is competitive with the other offerings and would be a strong choice for demonstration.

APPENDIX A: Request for Information

Request for Information
for
Techno-Economic Analysis (TEA)
for a
Carbon Capture System
for a
Shipboard Application

29 November 2022

MARAD Cooperative Agreement #693JF72150005
Document # DOC-LCE-0051

Prepared by:
Life Cycle Engineering
Process & Equipment Development Corporation

A-1 Background Discussion

The Maritime Administration (MARAD) of the United States has contracted with Life Cycle Engineering (LCE) to conduct a Marine Carbon Capture Technology Review and Techno-economic Analysis (TEA) for Shipboard Carbon Capture. A range of carbon capture technologies will be evaluated for both 1) ocean-going and 2) inland waterway vessels. The technology review has been completed.[2] **This request for information (RFI) is to provide data for carbon capture technologies for use in the TEAs.**

International efforts are underway in all industries to reduce or eliminate carbon emissions and the maritime industry is no exception. 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.

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. However, to make carbon-free fuels a reality, 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 carbon-free fuels and the associated infrastructure is in place.

Captured CO_2 would be purified and dried as required, compressed, liquefied, and stored on board ship. The stored CO_2 would be off-loaded at shore when the ship is fueled.

A-2 Techno-economic Analysis

The objective of the TEA is to estimate the 'first year' costs of CO_2 captured and CO_2 avoided for as many as five capture technologies. The analyses will be performed on two ships: one inland water vessel (MAP RUNNER) and one ocean-going vessel (SEAWAYS BRAZOS).[15,16] MAP RUNNER is a US inland river harbor vessel. SEAWAYS BRAZOS is a crude oil tanker built in 2012.

LCE's expertise is in the ship industry and requires input as detailed below from capture technology developers to perform this TEA.

A-3 Information Requested

Non-proprietary information is preferred but please indicate if proprietary information is provided. Please provide any additional information that is deemed pertinent to this request.

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[15] *MAP RUNNER, Local type - Details and current position - MMSI 367376640 - VesselFinder*. (n.d.). https://www.vesselfinder.com/vessels/details/367376640.

[16] *SEAWAYS BRAZOS, Crude Oil Tanker - Details and current position - IMO 9594731 - VesselFinder*. (n.d.). https://www.vesselfinder.com/vessels/details/9594731.

The target capture efficiency is 90%, however if the carbon capture technology ‘sweet spot’ is at a different capture efficiency, please cite that efficiency and provide the requested information for a system designed for the cited capture efficiency.

A booster blower will be provided upstream of the capture system to make the capture system ‘pressure neutral’. Assume that the capture system outlet pressure will be atmospheric and the inlet gage pressure will be equal to the system pressure drop.

The exhaust gas temperature is included with the exhaust gas conditions. It is assumed that all capture systems will benefit from lower temperatures. A cooler that is not part of the capture system will be provided to achieve the specified inlet temperature (must be 100°F or greater). Please specify the desired capture system inlet temperature.

Requested Information		
Block Flow Diagram		
Heat and Material Balance		
Inlet Temperature (must be 100°F or greater), °F		
Inlet Pressure (Required for outlet pressure to be 0 psig), psig		
Carbon Capture Efficiency, %		
Maximum System Turndown, %		
System Equipment Capital Cost		
Water Requirements		
Purity		
Flow Rate, pph		
Thermal Energy		
Steam Flow Rate, pph		
Steam Temperature, °F		
Steam Pressure, psia		
Shaft Power		
Mechanical Power, bhp		
CO2 Produced		
Purity, % CO2		
Temperature, °F		
Pressure, psia		
Contaminants		
Consumables		
Material		
Makeup Rate or Quantity per Replacement Period		
Approximate Envelope Dimensions and Weight of Equipment		
	(W x L x H)	(lb)
System 1		
System 2		
System 3		

Table A-1 – Requested Information

APPENDIX B: Company Comments

Seabound:

Since the submission of the Request for Information (RFI) for this study, Seabound has achieved a significant breakthrough in enhancing the design of onboard calcium looping CO_2 capture. This innovative system features modular sorbent storage in standard TEU containers, each functioning as both a gas-solid reactor and a solid sorbent storage unit. Unlike the previous approach, where solids needed to be conveyed to meet the gas, the solids now remain static within the container, and the exhaust gas is directed to react with the solids inside the containers. A manifold connects each container to the primary exhaust line, and control valves allow each container to be selectively activated for CO^2 capture.

This improved design offers several advantages, including a simplified approach that relies on moving exhaust gas instead of sorbent, eliminating the need for solids handling. The system is modular for efficient sorbent loading and unloading, resulting in reduced CAPEX, installation time, and retrofit costs. Moreover, it is fully modular and scalable, enabling owners to start with a few containers and expand the capacity over time.

PMW Technology:

Update since submission of Information in March 2023:

As part of the process of continuous process development, PMW Technology is pleased to provide additional information on a process development that was confidential at the time of the original information request.

The process revision significantly improves the separation step at low temperatures. This enhancement reduces the duty and size of low temperature heat exchangers and enables the product liquid carbon dioxide to be produced directly, eliminating the separate liquefication step.

The revised process simplifies the original design by recirculating the separation bed at low temperatures rather than warming all of it to recover the carbon dioxide. This reduces the cooling duty of the refrigeration system while exploiting the large improvement in heat transfer intensity offered by beads coated with solid carbon dioxide.

The impacts of this enhancement are a substantial reduction in capital cost, a reduction in complexity and lower overall energy consumption for the process. A further valuable benefit is a reduction in size and weight of the separation stage. The reduction in capital cost is estimated to be around 30%, including the elimination of the liquefication system. The improvement in energy consumption is in the order of 15-20% depending on the carbon dioxide content of the exhaust gases. These improvements are achieved while maintaining the advantage of high purity carbon dioxide product.