OIL AND GAS CLIMATE INITIATIVE

IS CARBON CAPTURE ON SHIPS FEASIBLE?

A REPORT FROM THE
OIL AND GAS CLIMATE INITIATIVE

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Stena Bulk

CONTENTS

Scope of the challenge

The transportation sector contributes 24% of global energy-related greenhouse gas emissions. Around 10% of that total comes from international deep-sea shipping. Because these ships operate outside of national coastal boundaries, they are governed by regulations negotiated and agreed upon by member states through the International Maritime Organization (IMO), a United Nations agency. In 2018 the IMO introduced a long-term vision to eliminate emissions from international shipping and particularly to cut emissions by 2050 to 50% or less of those in the baseline year of 2008.

Given the anticipated growth in shipping traffic, this goal is ambitious and will require the deployment of a number of technologies. While improved efficiency, propulsion aids and biofuels are expected to contribute towards the goal, additional measures will be necessary to ensure success. In addition to the use of hydrogen, ammonia and synthetic E-fuels as replacement fuels, carbon capture has emerged as a potential solution under investigation by several organizations. The basic concept is quite simple: take carbon capture technology currently in use in stationary applications and adapt it to remove carbon dioxide emissions from the exhaust gases of the large internal combustion engines that are heavily relied upon by the fleet.

To test this concept, in 2020 OGCI and Stena Bulk jointly conducted a study with TNO, a research institute based in the Netherlands,[2-5] and their subcontractors Conoship and CarboTreat. The aim of the study was to assess energy balances, fundamental physics and integration challenges.

Introduction

In their latest report, the IPCC states that meeting the ambition of the Paris Agreement to limit warming this century to 2.0°C requires immediate large-scale reductions in greenhouse gas emissions[1]. To achieve this, a wide portfolio of existing and new technologies must be deployed. This is especially the case for hard-to-abate industrial sectors, including marine shipping and aviation in transportation. While long-haul flights are likely to focus primarily on sustainable aviation fuels, marine shipping has more flexibility to explore unique options. One such option is the adaptation of stationary carbon capture technology to mobile applications. The Oil and Gas Climate Initiative and Stena Bulk recently partnered on a feasibility study to explore the potential of capturing carbon from the exhaust gases of the large internal combustion engines that large ships predominantly use for propulsion.

Ship selection

Stena Bulk operates a range of vessels, with the majority of the fleet concentrating on large bulk fluids such as crude oil and chemicals. Due to varying load requirements, the ships have an array of sizes and employ main propulsion engines of suitable power output. Although the primary fuels used by these ships are traditional heavy fuel oils and distillates, Stena Bulk does operate several liquified natural gas (LNG) powered vessels as well. Consequently, the team was able to assess three different ship and fuel combinations where Stena Bulk would make suitable data available. The three combinations were a medium range oil/chemical tanker, a Suezmax crude oil tanker (both running on heavy fuel oil), and an LNG carrier running on LNG.

When evaluating these options, it became clear that both detailed technical specifications and strategic considerations would play a role in the selection process. Among the technical details that were examined, key parameters such as sufficient deck space, the presence of potential fuel impurities like sulfur and the availability of heat energy in the exhaust gas were prioritized, while important strategic variables like representative fuels and relative industry impact also carried substantial weight. Table 1 captures these criteria and compares them across the three vessel types.

Table 1: Assessed criteria for selecting the candidate vessel from among the three options

EVALUATION CRITERION	MEDIUM RANGE TANKER	SUEZMAX TANKER	LNG CARRIER
Main engine type	7.2MW 2-stroke	15.7 MW 2-stroke	3x 3.8MW 4-stroke
Primary fuel	Heavy fuel oil	Heavy fuel oil	Natural gas
Space availability	Yes	Yes	Yes
Exhaust gas heat availability	Average	Poor	Good
Sulfur content/fuel impurities	High	High	Low
Representative of wider fleet	Yes	Yes	No
Impact of success	High	High	Low

From a technical perspective, the LNG carrier offered the simplest and most straightforward path to a feasible carbon capture system because it uses an engine type that delivers sufficient waste heat in the exhaust gas, uses a fuel with no impurities and offers infrastructure on board that could be beneficial when liquifying and storing the captured carbon dioxide. However, a system that proved feasible on this type of ship may not be easily adapted to other ships, so the relative impact of success would be low.

The other two options would likely prove more technically challenging, but a feasible system could be more readily adapted to similar ship types that represent the vast majority engaged in deep sea international shipping. Between the two, the Suezmax was expected to have less waste heat available. Since energy is required to operate any carbon capture system, more waste heat that can be sufficiently recovered reduces the need to seek supplemental sources of energy. Considering all these criteria, the team chose the Suezmax because it offered the highest potential impact if successful, even though it represented the greatest technical challenge .

Carbon capture technology

Similar to the process for selecting the candidate ship type, multiple post-combustion carbon capture technologies were considered for the analysis. Table 2 lists the four leading technologies along with key criteria used for assessing them. To assist in the selection process, the team identified key assumptions driven by type of ship, potential carbon dioxide off-loading sites and a projected timeline to demonstration. If the concept proved feasible, a likely next step would include a demonstration phase, so a technology's maturity was an important factor. Chemical absorption was viewed as having the highest maturity and immediately became the leading candidate.

A second concern involved the purity of the carbon dioxide delivered by the process. High purity levels reduce the energy and cost demands placed on a carbon dioxide liquefaction unit and ensure compatibility with existing carbon sequestration sites where purity level requirements typically must exceed 95% (with many requiring >99%)[6]. Capture rate was also a consideration, but played a relatively minor role since all of the technologies were capable of delivering reasonably high rates. Because the ship was fueled with heavy fuel oil, any capture system either needed to be insensitive to impurities such as sulfur compounds or have a way to manage them before they reached the capture unit.

Table 2: Assessed criteria for evaluating the most appropriate carbon capture technology

<table>
<tr><th>EVALUATION CRITERION FOR CANDIDATE SHIP</th><th>CHEMICAL ABSORPTION</th><th>ADSORPTION</th><th>MEMBRANE SEPARATION</th><th>CRYOGENIC SEPARATION</th></tr>
<tr><td>Technology maturity</td><td>High</td><td>Low</td><td>Low</td><td>Medium</td></tr>
<tr><td>CO_2 purity (est.) from process</td><td>99%</td><td colspan="2" rowspan="2">Purity and capture rate are linked. In general, CO_2 purity is low (80% for adsorption, 60% for membranes)</td><td>99.9%</td></tr>
<tr><td>CO_2 capture rate potential (est.)</td><td>90-99%</td><td>90-99%</td></tr>
<tr><td>Sensitivity to impurities</td><td>NOx & SOx</td><td>H_2O, NOx and SOx</td><td>NOx & SOx</td><td>potentially SOx, H_2O</td></tr>
</table>

Given these assumptions, the two most compatible technologies were cryogenic separation and chemical absorption. Although it offered competitive capture rates and purity levels, the cryogenic approach was expected to demand high rates of energy to bring the exhaust gas down to -140°C and remove the carbon dioxide at a relatively low 4% concentration. In the end the chemical absorption process using a liquid amine solution was selected as the best fit for the Suezmax due to its high maturity level, delivered purity compatible with off-loading sites and energy demand estimated to be lower than the cryogenic approach. Since many ships are fitted with exhaust scrubbers, it was assumed that use of such a system would limit exposure to impurities like sulfur oxides to a manageable level.

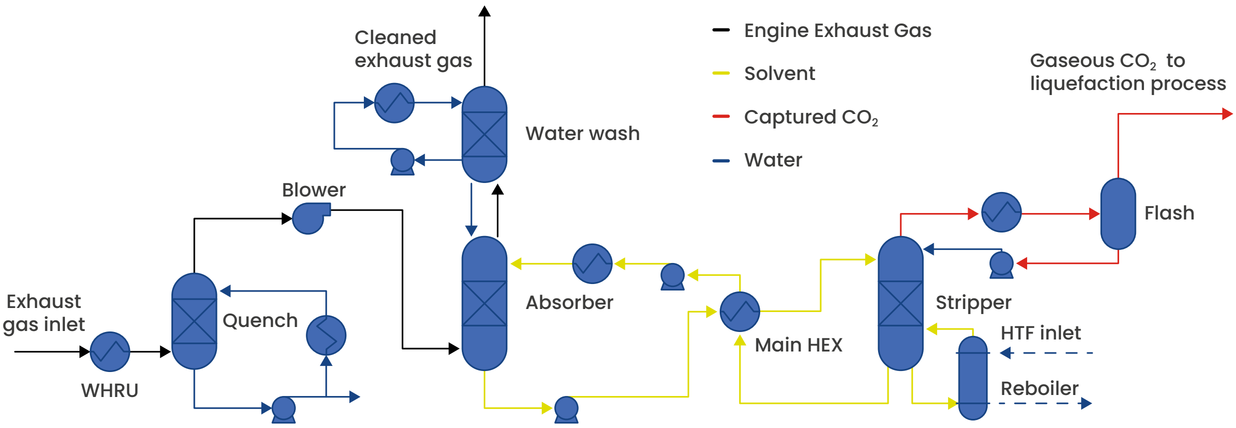
Although chemical absorption was seen as the best fit for the Suezmax feasibility study, this should not be misinterpreted to mean that other technology approaches are lacking merit. On the contrary, other technical approaches are likely to have benefits and drawbacks that make them more suitable for projects and vessels with different prioritization criteria. A thorough evaluation of these considerations and an assessment of best fit to various vessels was beyond the scope of this study.

System design and integration

The Suezmax tanker employs a 15.7MW MAN B&W 6S70ME-C8 two-stroke engine as its main propulsion unit, three 1MW Yanmar diesel generators for auxiliary power and a boiler system for crude oil transfer. All of these units contribute to carbon dioxide emissions from the ship so the carbon capture system must be designed to handle their collected exhaust gas. However, it was also expected that sizing and evaluating the system would require an iterative process, since the carbon capture system needs both electrical power supplied by the auxiliary engines and heat energy derived from either the engines or the boiler.

This requirement for energy creates a type of feedback loop where attempts to increase the capture rate may lead to additional fuel consumption and additional emissions that need to be captured. The net reduction in emissions is then calculated by subtracting the extra emissions needed to run the system from the overall amount captured and comparing that difference to the original level generated under normal operation. This net reduction is sometimes referred to as the amount "avoided" to distinguish it from the gross amount of carbon dioxide that the capture system is removing from the exhaust stream.

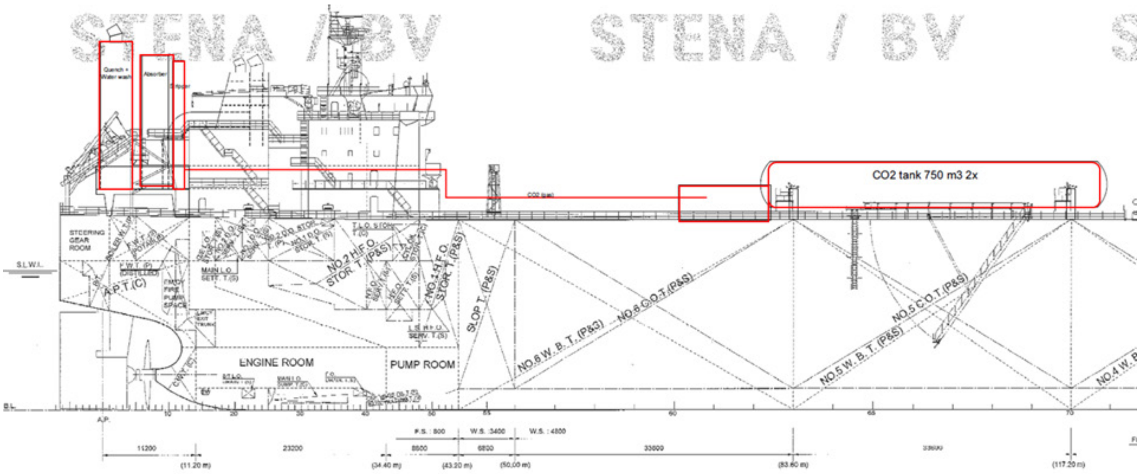
Figure 1: Schematic showing major components of the carbon capture system



The conceptual design (Figure 1) was derived from stationary carbon capture applications and assumes that the system begins downstream of any waste heat recovery unit connected to the engines. The first stage of the system uses water quenching to lower the temperature of the exhaust gas to approximately 40°C, a temperature at which carbon dioxide is readily absorbed in the next stage by monoethanolamine (MEA), a first-generation amine solution widely used in carbon capture applications. A blower compensates for back-pressure induced by the overall system to avoid negative performance impacts on the two-stroke propulsion engine. The cooled exhaust gas then enters the absorber column where it is exposed to the amine sorbent and carbon dioxide is absorbed into the solution. Most of the volatile amine carried out of the absorber is removed from the exhaust gas by the water wash and returned to the column.

The carbon dioxide-enriched amine is then pumped out the bottom and sent through a heat exchanger to scavenge energy from the carbon dioxide-lean amine returning from the stripper. At the bottom of the stripper the temperature of the amine solution is increased to ca. 120°C at two bar. The reboiler raises part of the amine solution to the boiling point in order to introduce sufficient vapor to strip the carbon dioxide from the solvent. Concentrated carbon dioxide and water vapor exit the top of the stripper and are then cooled and flashed to remove residual water and amine, which is returned to the main loop. The almost pure gaseous carbon dioxide is then sent to a final quench station where remaining impurities are removed and finally to a liquefaction system where it is compressed, liquefied and pumped into holding tanks at a pressure of 16 to 20 bar.
To evaluate the potential integration of the system onto the ship, a full-scale case with an assumed capture rate of 50% and a 21-day length of voyage was considered and sized accordingly. Figure 2 shows the approximate size and location of the main components of the system with the quench, absorber and stripper columns mounted on the stern near the engine exhaust stack and the liquefaction system and liquid carbon dioxide storage tanks located on deck forward of the bridge, but aft of midship. The columns ranged in diameter from one metre to four metres and were placed near the centre line of the ship and kept to a maximum height under 18 metres to avoid causing blind spots for lighting and radar. Visibility from the bridge was not expected to be compromised.

Figure 2: Profile of a Stena Bulk Suezmax tanker with carbon capture system, liquefaction system and storage tanks superimposed



The mass of the system was estimated to be just over 2,500 t when fully loaded with carbon dioxide. This represented the maximum deadweight capacity lost to the system. The combined volume of the tanks was estimated at 1,500 m^3 and space was easily found on deck. For other vessel types, such as container ships, the size and location of the storage tanks will be of much greater importance due to more limited deck space. Of greater concern for the tanker was the potential impact on stability, but the metacentric height was calculated to only decrease from 5.2 m to 5.0 m and was therefore deemed insignificant. Safety concerns revealed by a HAZID analysis primarily focused on human exposure to the solvent (MEA) and the concentrated carbon dioxide, both of which were identified as manageable through appropriate engineering and safety protocols. Hazards related to liquefaction and storage of the carbon dioxide were addressable through rules listed in the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk.

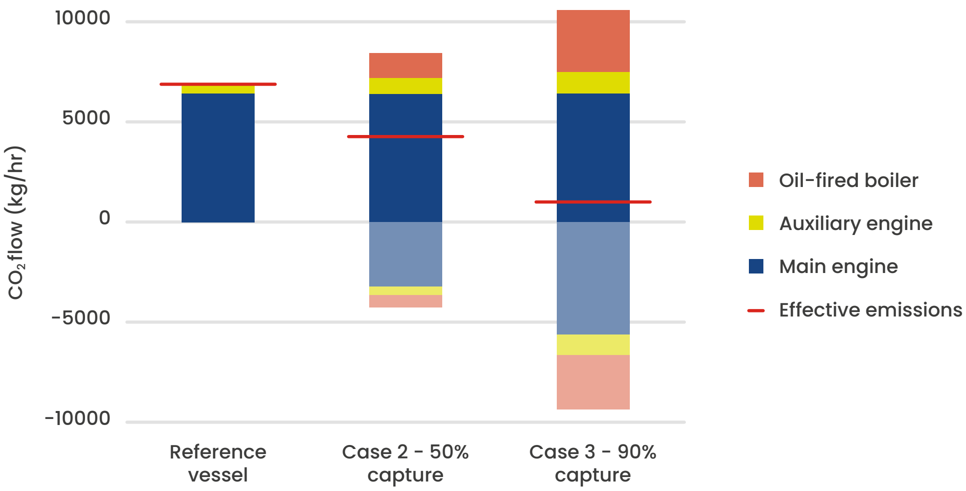
Performance analysis

Since the target capture rate directly affects the energy demand from the system, three distinct capture rates were considered during the performance evaluation phase: 1) the maximum amount of carbon dioxide capturable when no additional heat energy is needed from the engines to drive the absorption and desorption processes; 2) 50% of all carbon dioxide captured from the exhaust gas; and 3) 90% of all carbon dioxide captured from the exhaust gas. To simplify the calculations, the ship was assumed to be traveling at a set speed and an engine power of 75% of maximum continuous rating (MCR). The energy analysis included all electricity needed to operate the compressors, pumps, supplemental exhaust gas blower, heat energy delivered by the main propulsion engine, auxiliary engines, and oil-fired boilers.

Using only the available heat energy from the main propulsion engine, case 1 showed that approximately 8% of the carbon dioxide emissions could be captured. This relatively low figure hints at the lack of available waste heat energy that can be scavenged from the efficient, slow-speed two-stroke engine. Achieving any level of carbon capture beyond this point would require additional heat sources coming primarily from the auxiliary engines and oil-fired boilers.

Figure 3 shows that the analysis of cases 2 and 3 bore this out. As the capture rate increased, the amount of energy needed increased. This could only be supplied through excess fuel burned in the auxiliary engines and oil-fired boilers. Compared with the reference case, this amounted to 22% and 53% more fuel consumed for cases 2 and 3, respectively. The red line shown for each case represents the final carbon dioxide avoidance, or the overall reduction in carbon dioxide exiting the exhaust stack, once the emissions from the additional fuel burned were considered.

Figure 3: Comparison of CO_2 emissions from the reference case and the 50% and 90% capture rate cases



Low exhaust gas temperatures from the main propulsion engine primarily drive the need for additional fuel consumption in the auxiliary engines and boiler. However, these engines were designed and optimized to deliver high efficiency and not to support the implementation of a carbon capture system. Consequently, measures to recalibrate engine performance or optimize the waste heat recovery units to complement a carbon capture system have not been explored, so the figures shown here may be assumed to be a worst-case estimate.

Economic analysis

For any commercial endeavor, capital and operating expenses determine the viability of any proposed technical solution, so it is important to provide initial estimates for these numbers. The capital expenditure (capex) estimate was built by analyzing the current individual costs for the main components needed in the carbon dioxide removal, liquefaction and storage processes. Figure 4 shows a breakdown of these equipment costs based on information provided by AspenPlus's Aspen Capital Cost Estimator v11. The storage tanks, although not complex, contribute significantly to the costs. Volume production to meet widespread industry demand would likely lead to reductions in these component costs, but the magnitude of such reductions is difficult to assess. Component costs are not the only contributor to overall capital expenditures and Figure 5 shows the estimated costs when engineering, procurement and construction (EPC) and contingency costs are included.

Figure 4: Estimated component costs for the carbon capture system analyzed in cases 2 and 3

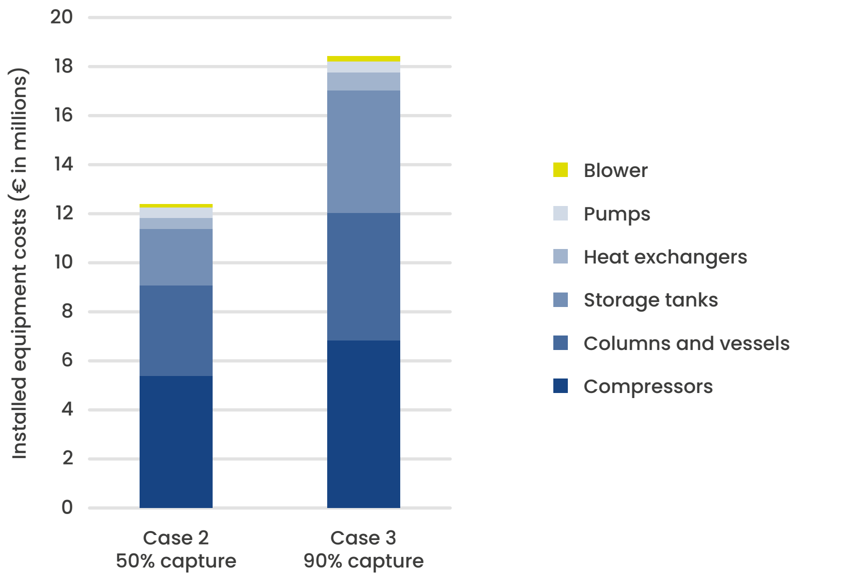
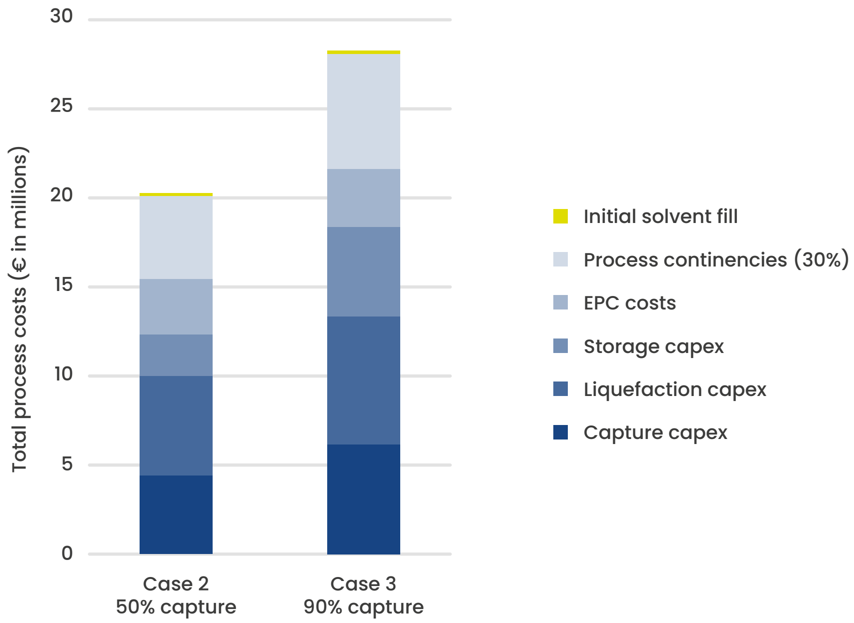


Figure 5: Total capital expenditure estimates for a 50% and 90% carbon capture system installed on a Suezmax vessel



Operating expenses are equally important and the impact of the excess fuel burned can be substantial. Table 3 provides a breakdown of estimated fixed and variable operating expenses for cases 2 and 3. The variable expenses associated with producing the additional energy for the capture system dominate and the total numbers add nearly 13% and 25% to a reference vessel's existing operating expenses.

Table 3: Fixed and variable operating expenses

FIXED AND VARIABLE OPERATING EXPENSES € (in thousands)/YEAR	CASE 2 (50%)	CASE 3 (90%)
Labor	100	100
Maintenance	153.6	153.6
Insurance	120.4	120.4
Overhead	18.4	18.4
Heat demand (excess fuel)	474	1,187
Electricity	157	299
Solvent replacement	15	30
Total	**938.4**	**1,808.4**

A key element missing from this analysis is the port-side infrastructure necessary to off-load and process the captured carbon dioxide. Although some ports and locations are equipped to handle shipments of carbon dioxide for industrial use and large-scale recycling and sequestration operations, most ports are not set up to manage this process. The capital investments needed to build such infrastructure have not been analyzed here and any associated costs have not been factored into the estimated numbers.

Meeting IMO's 2030 targets

Given the above analysis and to frame the results better within the context of the shipping industry, a case was specifically constructed to evaluate how the system could work if used to meet the impending IMO carbon dioxide target for 2030. This target would require ships like the current Suezmax to reduce their emissions by about 25% relative to today. To ground the results even further, several assumptions were made to understand what the impact might be under real operating conditions (when, for example, the engine is not operated at its 75% MCR loads continuously), with actual sailing profiles considered, with discharge and sequestration sites assumed to be immature or not readily accessible, and with the investment or retrofit amortized over different numbers of years. Put another way, the figures presented in Table 3 together with the overall capital expenditure were converted into the added daily running costs and the $/t$CO_2$ cost of avoidance that shipowners could use to compare mobile carbon capture to other options to meet 2030 (or other) targets.

Table 4: Running costs and returns if aiming for a 25-30% avoidance rate to meet IMO's 2030 target

	If capture system is always used when sailing	If used 50% of the time when sailing	50% usage until 2025, increasing to 100% by 2030
TOTAL CO_2 (MT/Y)			
CO_2 produced	35,540	35,540	35,540
Emitted/vented	24,891	30,216	28,299
Captured	10,649	5,325	7,241
% captured (avg. over lifetime)	30%	15%	20%
Total investment over lifetime (12 years)	**$18.5m**	**$17m**	**$17.6m**
CHANGES TO RUNNING COSTS ($/D)			
Total extra running costs	4,727	4,151	4,358
- of which due to fixed costs	4,232	3,903	4,022
- of which due to variable costs	495	248	337
- of which due to sequestration	438	219	298
$/tCO$_2$	**175**	**297**	**232**
OVER 20 YEARS LIFETIME			
Total extra running costs $/d	4,101	3,524	3,732
$/tCO$_2$	153	254	201
OVER 20 YEARS WITH A SUBSIDY OF $35/TCO$_2$			
Total extra running costs $/d	3,080	3,014	3,038
$/tCO$_2$	106	207	153
OVER 20 YEARS WITH A SUBSIDY OF $35/TCO$_2$ AND 50% REDUCTION IN CAPEX			
Total extra running costs $/d	1,898	1,905	1,903
$/tCO$_2$	65	131	96

Given that a 25-30% capture rate requires less additional heat to run the system compared with the 50% or 90% cases (2 and 3), the largest contributor to daily running expenses becomes the amortization schedule for the capex and fixed operational costs over the ship's remaining life (12 years, in the first scenario towards the top half of Table 4). Thus, if retrofitted to a ship with around 12 years of potential trading life left, daily costs go up by about 20-30%, mostly due to capex. This could be reduced further if the owner operates the ship for 20 years, receives a tax subsidy for the avoided carbon dioxide and/or can reduce capex substantially.

Conclusion

We used a large oil tanker as a test case to adapt carbon capture technology for use onboard ships. The process appears to be technically feasible with no major barriers emerging during the course of the study. Since the oil tanker was powered by a highly efficient, two-stroke engine with low energy availability in the exhaust gas, the test case represents one of the most challenging applications and leads to an increased consumption of fuel to power auxiliary engines and an oil-fired boiler that delivers the necessary energy to run the capture system.

Optimization of the engine and/or waste heat recovery units to be more compatible with a carbon capture system may reduce the need for additional fuel consumption. Vessels using engines with more waste heat availability may prove more feasible with the system as designed. Developments in carbon capture technology that reduce the carbon dioxide separation energy would have a significant impact on energy demand and this should be a primary focus for research and development teams.

Although we demonstrated technical feasibility, capital and operating expenses remain high. Capex is driven by the relatively high costs of the storage tanks, compressors and columns, while the cost of excess fuel burned is the highest contributor to operating expenses. These costs are a substantial hurdle to deployment and cost reductions in several key areas would be needed for the long-term viability of the technology. Commodity prices for captured carbon dioxide may offset some of these costs, but this is difficult to assess without clear guidance on regulations governing carbon pricing.

As the marine industry sets course for 2030 with an ambition to meet the IMO targets for greenhouse gas emissions, other carbon reduction technologies are likely to remain more attractive. As those more attractive solutions are deployed and the benefits realized, more aggressive solutions will need to be considered to meet long-term decarbonization goals. It may be more appropriate to compare marine carbon capture to other solutions requiring long-term investment and infrastructure build-out, such as ammonia and hydrogen. By 2030 more mature networks and infrastructure to process and sequester large volumes of carbon dioxide are expected to be in place. Utilizing those systems for the off-loading of carbon dioxide captured on ships may prove attractive. Regardless, if the costs of marine carbon capture can be sufficiently addressed, it could play an important role in a multi-pronged effort to meet the challenge of decarbonizing the marine industry.

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OIL AND GAS CLIMATE INITIATIVE

WHAT IS THE OIL AND GAS CLIMATE INITIATIVE?

The OGCI is a CEO-led initiative that aims to accelerate the industry response to climate change. OGCI member companies explicitly support the Paris Agreement and its aims.
As leaders in the industry, accounting for almost 30% of global operated oil and gas production, we aim to leverage our collective strength and expand the pace and scope of our transitions to a low-carbon future, so helping to achieve net zero emissions as early as possible.

Our members collectively invest over $7B each year in low carbon solutions. OGCI Climate Investments was set up by members to catalyze low carbon ecosystems. This $1B+ fund invests in technologies and projects that accelerate decarbonization in oil and gas, industry and commercial transport.

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