The role of onboard carbon capture in maritime decarbonization

A case study of the largest shipping segments, main carbon-based fuels, and full and partial application as part of a newbuild or retrofit

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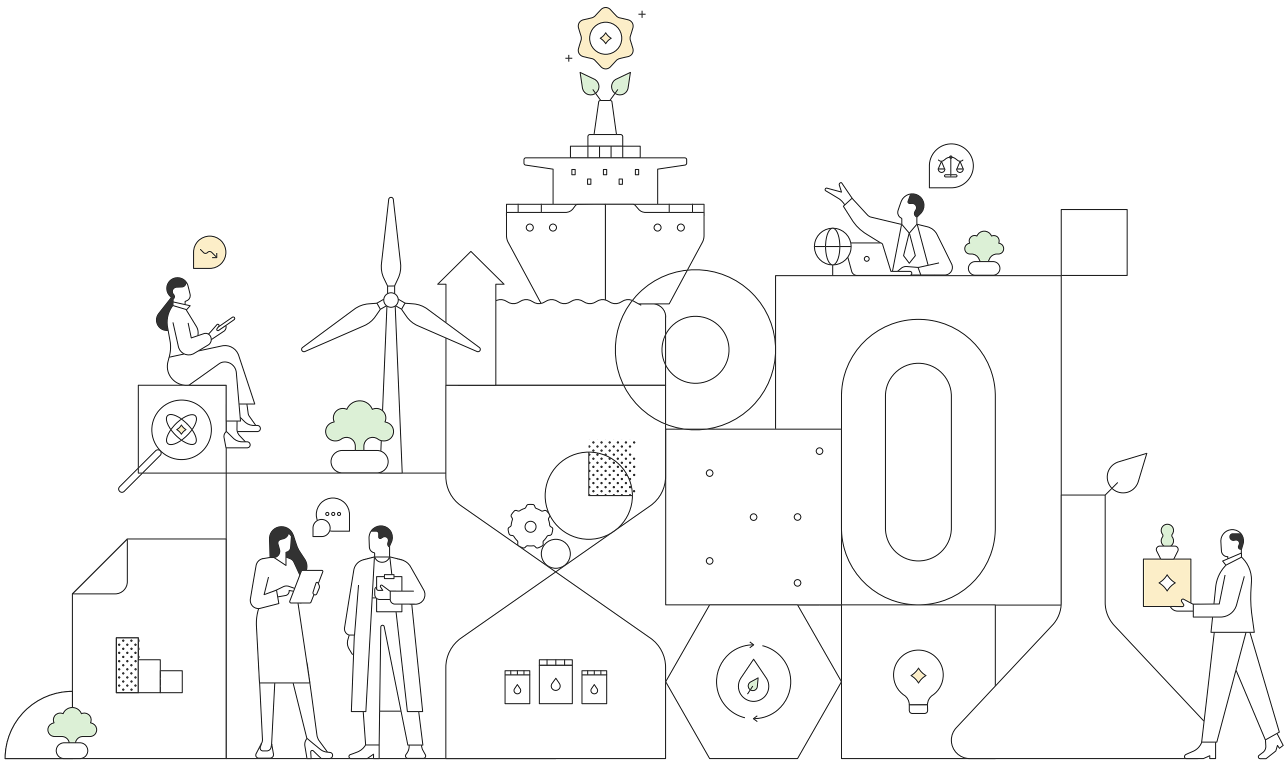

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

This paper presents the results from a work package on onboard carbon capture completed as part of the Green Fuels Optionality Project (GFOP) at the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS).

The GFOP studied the key design considerations and trade-offs associated with different fuel choices and vessel configurations. For the largest shipping segments (i.e., container, bulk, tanker), the project provides conclusions on attractiveness, cost, and timing of converting existing and alternative fuel-prepared vessels, technical guidance on ship design considerations, and the greenhouse gas impact of a conversion.

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Executive summary

Onboard carbon capture (OCC) is being considered as a technology that will play a role in decarbonizing shipping, in combination with energy efficiency and alternative fuels. OCC can be applied to all carbon-containing fossil, electro, and biofuels and, as a result, could play a mid- to long-term role in maritime decarbonization. However, the applicability of OCC depends on several factors including OCC technology development, commercial viability, alternative fuel prices and availability, and future emission-related regulatory requirements.

To gain a better understanding of the role of OCC in maritime decarbonization and assess OCC's business case for different vessel types and sizes, we analyzed the applicability of OCC to the largest shipping segments (container, bulk, and tanker), main carbon-based fuels and full and partial application as part of a retrofit or newbuild. For a series of case studies, we evaluated technical feasibility, carbon emission reduction performance, design integration, and CO_2 abatement costs. For a very large crude carrier (VLCC) newbuild, the best business case studied, CO_2 abatement cost ranges from $220-290/ton$CO_2$ with a tank-to-wake effective CO_2 emission reduction of 74-78%.

Based on the case studies completed, we concluded that:

- OCC with chemical absorption is technically feasible and expected to reach commercial availability by 2030,
- Additional OCC energy requirements lead to higher total fuel consumption (up to a 45% increase),
- Potential application of OCC shows the most promise for newbuilds as retrofits are costly and can require major modifications,
- Partial carbon capture typically leads to higher CO_2 abatement costs due to high initial CAPEX, and
- OCC on large tankers has the best business cases while small bulk carriers have the most challenges.

Although the emissions reduction potential of OCC is significant, currently its CO_2 abatement costs are high. Still, with further development OCC could play a role in the mid-term to reduce the emission intensity of existing fossil-fueled vessels. Further analyses and developments are required to maximize OCC emission reduction and minimize costs, as well as developing business models that would allow utilization and/or storage of the carbon captured onboard vessels. As a continuation of this work, the MMMCZCS has initiated an onboard carbon capture working group to study additional OCC technologies, applications, and business models.

Although OCC technologies are still in development, they will be commercially available soon and can provide significant emission reductions. As a result, ship owners aiming to decarbonize should assess their mid-term emission reduction targets and consider including OCC if it is an option for their vessel types, sizes, and trades.

1 Introduction

On shipping's path to net-zero carbon emissions, onboard carbon capture (OCC) is a technology that is being considered in parallel with energy efficiency and alternative fuels.

With application to all carbon-containing fossil, electro and biofuels, OCC can potentially have a mid- to long-term role in maritime decarbonization depending on several factors like emission-related regulatory requirements including market-based measures, alternative fuel prices and availability, and OCC technology development and commercial viability. In the mid-term from around 2030, OCC could be a solution to reduce emission intensity of existing fossil-fueled vessels (bridging technology). In the longer-term, OCC can be used to capture and reuse green carbon dioxide (CO_2) as part of a methanization cycle.

OCC has been criticized as an inefficient and costly way to reduce carbon emissions when taking a more holistic perspective. For example, point source carbon capture on shore will be more cost-efficient with lower abatement costs and less impact than capturing carbon onboard vessels. However, our focus is on decarbonizing the maritime industry and OCC should be considered within this context. It can also be argued that in the mid-term it is more cost-efficient to use blue ammonia as a fuel where CO_2 is captured and stored as part of the fuel's production and low amounts of carbon are emitted directly from the vessel. While this is potentially a good option for newbuilds or in some cases as a fuel conversion, we forecast that fossil-based fuel oil and liquefied natural gas (LNG) vessels will remain in the fleet for decades as the industry transitions towards our net-zero target in 2050. Certain emission regulations will need to be complied with and potential market-based measures including a price of carbon will trigger the need to reduce emissions from fuel oil and LNG vessels in the mid-term.

For fossil-fueled vessels, there are three main options to reduce emissions. Energy efficiency initiatives typically have positive business cases (negative abatement costs) and should be implemented as soon as possible. The other option is to pay for alternative low carbon fuels, which in some cases could require additional capital investment associated with fuel conversion. The third option is to use onboard emission reduction technologies like OCC. As regulatory requirements get stricter and the price of carbon increases, regulatory compliance, and commercial viability of some vessels during the 2030s might be challenged. There could be a scenario where all energy efficiency measures have been implemented as much as possible and alternative fuels are expensive and limited in availability. This could trigger a gap in solutions where onboard carbon capture can be considered.

To get a better understanding of the role of OCC in maritime decarbonization and assess OCC's business case for different vessel types and sizes, we studied the three largest shipping segments (container, bulk, and tanker), main carbon-based fuels and full and partial application as part of a retrofit or newbuild. Technical feasibility, carbon emission reduction performance, design integration and financials were evaluated. CO_2 abatement cost and emission reduction potential were estimated for a very large crude carrier (VLCC) case to provide a general indication relative to other solutions like energy efficiency initiatives and alternative fuels.

2 OCC Technology

CO_2 can be separated or captured both pre- and post-combustion.[1] Pre-combustion capture uses reforming to separate gases into mainly hydrogen and CO_2. This process is used when reforming carbon-containing fuels to hydrogen for onboard use in fuel cells. Post-combustion capture utilizes the exhaust gas to capture and store the CO_2. There are several different exhaust gas (post-combustion) carbon capture technologies and CO_2 storage types,[2] which could be considered for onboard use. Preconditioning to increase CO_2 concentration is needed for some carbon capture technologies. For this study, post-combustion liquid amine absorption with liquid CO_2 storage was used. The full OCC system consists of a liquid amine absorption capture unit, liquefaction unit and storage tank (Figure 1).

The MMMCZCS expects the amine-based absorption OCC system to reach a technology readiness level (TRL) 9 around 2028-2030 (Figure 2). While the capture technology has been tested onboard a vessel, the full integrated system including onboard liquefaction and storage has not been tested in the marine environment. However, current liquified CO_2 carrier projects that include onboard liquefaction and storage are expected to demonstrate these technologies onboard vessels by 2025. The need for exhaust cleaning prior to carbon capture has been identified as a potential issue for use with heavy fuel oil and would require development based on existing technologies.

While carbon capture technology development is advanced, there are major risks that must be mitigated prior to large-scale commercial application onboard vessels. The main risks include additional onboard energy demand, potential cargo loss, delay in development of a regulatory framework or market to get credit for CO_2 reduction, and a lag in infrastructure development on shore. See Figure 3 for an overview of the main risks and potential mitigation measures identified by the MMMCZCS that can contribute to advancing the development of OCC technology onboard vessels.

[1] ABS "Carbon capture, utilization and storage" August 2021
[2] Potential technologies for OCC include membrane separation, adsorption separation, liquid absorption separation and solid absorption separation. CO_2 storage types include single component (dry ice, liquid CO_2, or supercritical CO_2), solid containing CO_2 (adsorbent or absorbent) and multicomponent liquid (Shipping Zero Emission Project "Roadmap to Zero Emission from International Shipping" March 2020)

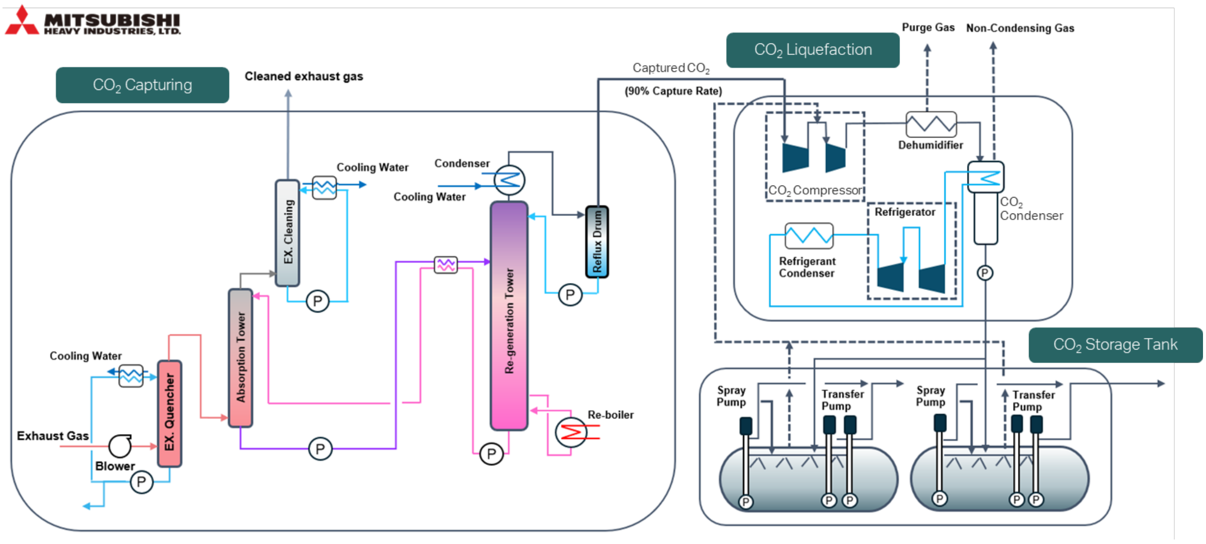


Figure 1: Onboard carbon capture system composition (Source: Mitsubishi Heavy Industries).

3 Case studies

We completed a series of case studies covering the installation of OCC on low sulfur fuel oil (LSFO)-, LNG- and methanol (MeOH)-fueled vessels within the three largest segments (container, bulk, and tanker).

Figure 4 provides an overview of the vessel types and sizes considered and the associated fuel as well as if the study was focused on retrofitting an existing vessel or a newbuild design. While most of our studies focus on newbuild integration, the VLCC case study also includes a study of retrofitting a partial and full OCC system on an existing vessel. We did not consider integration of OCC on LNG bulk carriers due to significant cargo losses. As endurance and ship speed (propulsion energy) have a major impact on the ship's arrangement, these were carefully defined before starting each case study. Next, we considered the required dimensions for CO_2 storage tanks and their ideal location. Loss of cargo (volume and weight) when installing an OCC system was also an important consideration. In some cases, CO_2 storage tanks must be installed in cargo holds, resulting in cargo loss. For this study, loss of cargo weight was calculated as the increase of lightweight due to the carbon capture system plus the weight of captured CO_2 minus the weight of consumed fuel.

4 Integrating OCC on tankers, bulk carriers, and container vessels

In this section, we outline the performance, design integration, and financial impacts of integrating OCC on a VLCC, long range 2 (LR2) tanker, 82,000 DWT bulk carrier, 205,000 DWT bulk carrier and 15,000 TEU container ship newbuilds. Newbuild

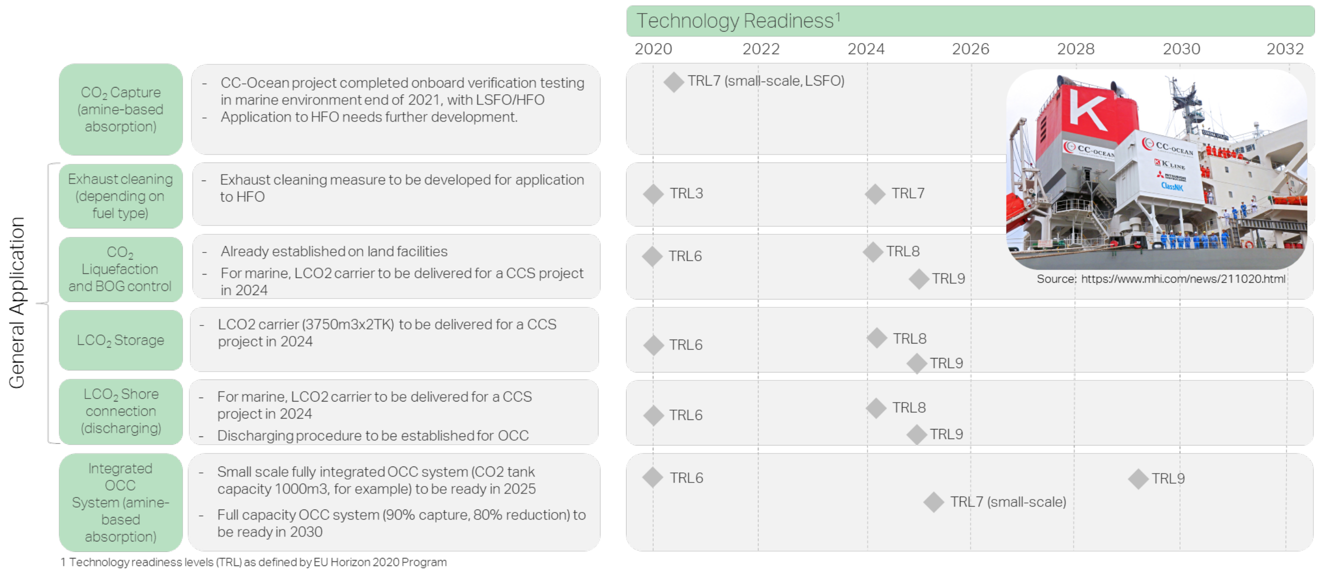


Figure 2: OCC technology development timeline.

Subject	Risks	Potential mitigations
Capture Rate	- Maximum onboard capture rate currently 82%, which is lower than onshore application - Validation of CO_2 capture rate	- Further improvement of onboard capture rate - Accurate measurement and recording systems
Energy Consumption	- Capture, liquefaction and storage requires large amount of additional energy (up to +40%)	- Optimization with fuel type auxiliaries (like LNG) - Reduction of power for the liquefier (cryogenic decompression?)
Ship Integration	- High volume and weight of capture and storage systems leads to potential cargo loss - Adaptation of shore- to marine-based environment requires additional considerations - Pre-treatment is needed depending on fuel such as denitration, desulfurization, and particulates) - (especially SO_3)	- Arrangement of engine casing and engine room incl. height of equipment (absorption tower and reclamation tower) - Motion and vibration countermeasures for equipment - Handling of amine solution, saltwater damage countermeasures - Exhaust gas pre-treatment technology
Operations	- Additional systems requires onboard management, maintenance, safety and handling requirements - Availability and cost of amine solution	- Additional crew to manage system and safety guidelines - Determine how specialized the amine solution needs to be and associated impacts
Cost	- Full application can be too costly (CAPEX 25-70% of newbuild price)	- Optimization of target capture rate as a countermeasure to satisfy CII by retrofitting, combination with fuel conversion or optimization based on base ship design - Cost reduction as part of technology development process
CO_2 Utilization	- Limited CO_2 handling infrastructure - No framework to get credit for CO_2 reduction and limited market value	- CO_2 handling with shore facilities - Inclusion into future regulatory framework, tax and credit schemes setup,

Low risk remains | Medium risk remains | High risk remains

Figure 3: OCC main risks and mitigation measures.

design integration studies focused mostly on full application and maximum carbon capture rates; however, some analysis was conducted to understand the impact of a partial installation onboard a newbuild. In Section 5, we provide detailed results for the VLCC case study. Snapshots of the other case studies can be found in the Appendix.

4.1 Performance

The main performance indicators for OCC technology are the carbon capture rate and the additional energy. In our study, we considered:

- The maximum capture rate of the system to be 82%. The capture rate in land-based plants is generally considered about 90%. Here, we took a conservative value for marine application considering tolerance of the plant (both engine and capture unit) and loss in the liquefaction plant and boil off gas control system. The capture rate can be improved up to 90% with maturity of the system.
- Additional energy is estimated considering the base ship design and required capture rate. The additional energy consists of electrical energy for systems like circulation pumps and liquefaction as well as heat energy for CO_2 separation.

Based on the above, we calculated the effective emission reduction to account for the increased energy consumption of the OCC system. Figure 5 shows the carbon reduction performance of full application at 82% capture rate for all case studies. For the LSFO fuel type, the OCC system increases CO_2 emissions by 40-45%. With an 82% capture rate, the effective emission reduction compared to the base ship CO_2 emissions is around 75%. LNG-fueled vessels have an advantage because they save energy on liquefaction, mitigating the increased

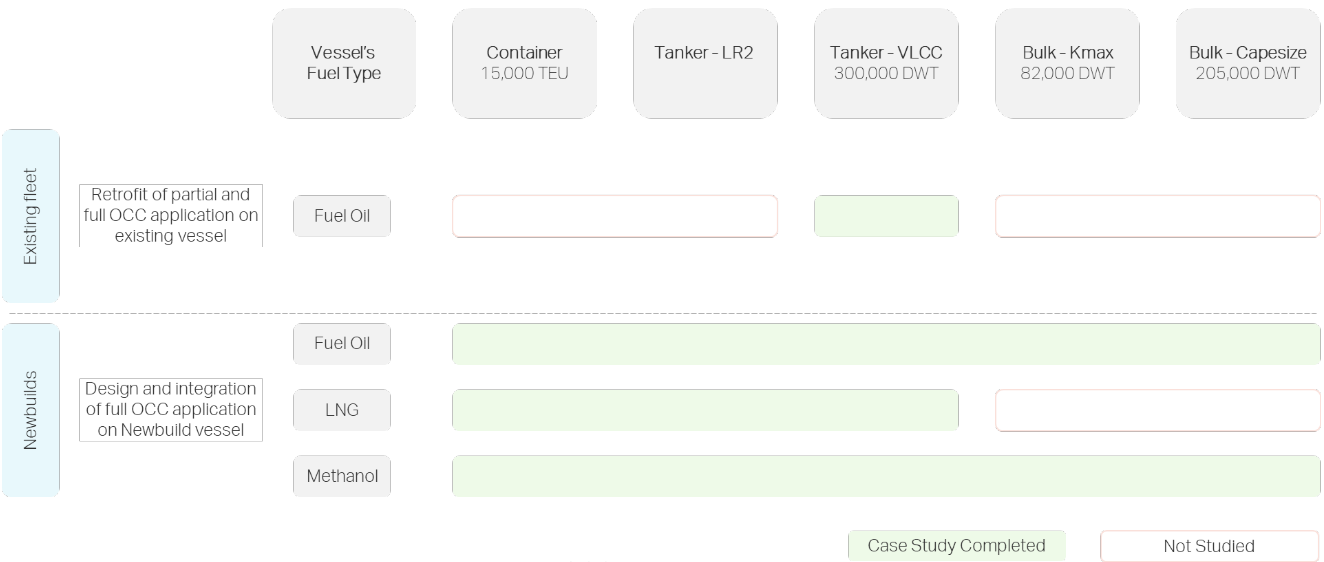


Figure 4: OCC case studies overview.

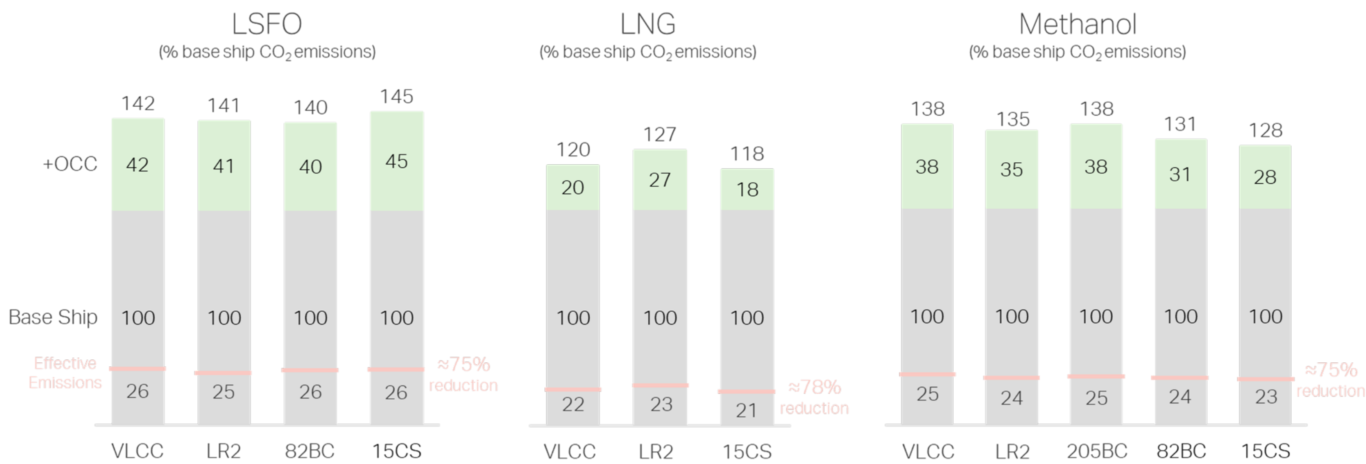


Figure 5: Carbon reduction performance - full application at 82% capture rate.

82BC = 82,000 DWT bulk carrier, 205BC = 205,000 DWT bulk carrier, 15CS = 15,000 TEU container ship

energy requirement from the OCC system. Other differences between LSFO and MeOH CO_2 reductions are mainly related to carbon factors of the fuels.

Carbon reduction percentage does not vary much by vessel type, but fuel selection does have an impact. LNG-fueled vessels can achieve around 78% effective emissions versus around 75% on LSFO and MeOH vessels. On an annual basis, CO_2 captured can range from around 22,000 tons for an LR2 tanker to over 97,000 tons for a 15,000 TEU container vessel. See the Appendix for further details on annual carbon emissions and captured carbon.

4.2 Design integration

Major modifications typically needed to integrate an OCC system onboard include an enlarged casing, capture unit, liquefaction unit, CO_2 storage tanks, increased auxiliary power, and increased steam generation. Amine solution supply systems, activator and demineralized water is also needed. Stability, strength, visibility, and mooring checks also need to be analyzed.

Tankers are impacted the least by the OCC system installation because CO_2 tanks can be installed on the deck. To minimize impact on longitudinal strength, two tanks can be located on the forward part of the deck. However, this tank location means that the height of the navigation bridge needs to be increased from the original design to satisfy visibility criteria. CO_2 tanks also increase maximum longitudinal bending moment of a vessel by 5-10%. Depending on strength margin of the original design, hull reinforcement or operational limitation may be necessary. In the VLCC-LSFO-OCC case, total CO_2 tank capacity is 10,400m^3, which is larger than that of a typical dedicated CO_2 carrier currently under construction (7,500m^3).

Integration of OCC onboard bulk carriers presents the most challenges. Initially, we studied a 205,000 DWT (Capesize) bulk carrier. An Australia-Japan round trip (23,000nm) was used to dimension fuel and CO_2 tank capacities. For this ship, it was difficult to arrange both the LNG fuel supply system and OCC system due to space limitations. Therefore, the LNG case was not studied. Furthermore, it was challenging to arrange the OCC system with full performance (82% capture rate) for the main engine part only. For these reasons, LSFO+OCC (50%) and MeOH+OCC (50%) were studied. Also, a full performance study was completed for MeOH, where one cargo hold is used for CO_2 tanks.

An 82,000 DWT bulk carrier has less space for the OCC unit and integration is more challenging. It was difficult to arrange allowing for the main engine part even for 50% performance case. Therefore, one cargo hold was used for the CO_2 tanks.

For the 15,000 TEU container vessel, a Rotterdam-Singapore single trip (8,300nm) was used as the reference route with CO_2 receiving facilities located in both Rotterdam and Singapore. A round trip case was also investigated but proved difficult due to a large increase in hull girder shear force (+20%) and stability problems caused by increased CO_2 storage requirements.

Therefore, the results for a round trip case are not shown. Installation of the OCC unit and CO_2 tanks in the cargo hold causes slot losses (for example, 1,200 TEU for the LSFO case). LNG or MeOH fuel tanks do not influence cargo slots as these tanks are not located where containers are stored.

A summary of integration considerations for all case studies is provided in the Appendix. Tankers allow for easier integration (with CO_2 tanks on deck) and minimal impact on cargo capacity. Bulk carriers and container vessels present more integration challenges that can lead to significant cargo loss. Ship integration and cost impacts become larger for smaller vessels, so large tankers provide the best business case.

4.3 Financials

Capital expenditures (CAPEX) were calculated for each case study completed and divided into the main cost drivers including capture, liquefaction, tanks, outfitting, piping and design. Also, the CAPEX relative to the vessel's newbuild price was calculated to provide perspective. In absolute terms, LNG is the least expensive and LSFO is the most expensive.

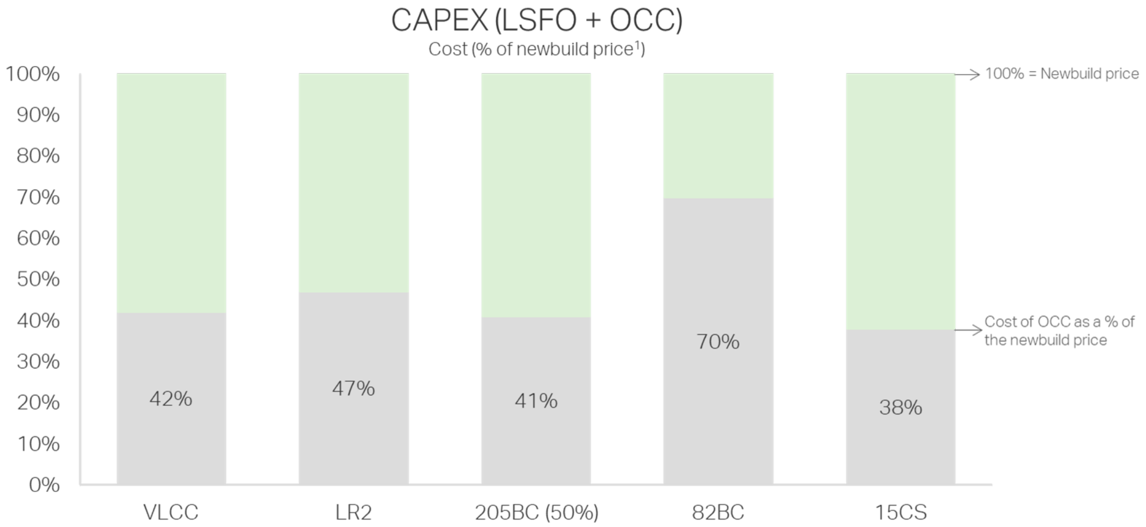


Figure 6: CAPEX as a percentage relative to newbuild price for LSFO+OCC by ship type.
82BC = 82,000 DWT bulk carrier, 205BC = 205,000 DWT bulk carrier, 15CS = 15,000 TEU container ship.
[1]Onboard-related financials only; excludes onshore infrastructure, CO_2 transportation, storage value and carbon tax credits.

Tankers and bulk carriers have similar breakdown percentages. Liquefaction for larger systems like on container vessels becomes a smaller share of the total percentage. Smaller vessels are more difficult and costly to integrate OCC. Larger tankers and container vessels are more cost effective. Revenue loss due to cargo reduction was not considered and will impact mainly bulk carrier and container designs.

See Figure 6 for CAPEX as a percentage relative to newbuild price for the LSFO+OCC configuration by ship type. While on average it costs around 40% of the newbuild price to install OCC, it can be as high as 70% for smaller bulk carriers. The major driver of additional operating expenses (OPEX) is related to the fuel consumption for the OCC system, which can be more than 70% of the total additional OPEX. Excluding fuel cost, OPEX is around \$0.5-2M per year depending on vessel type and size.

5 Case study: Integrating OCC on a VLCC

The VLCC case study provides a detailed example of newbuild integration, the impact of partial application, and newbuild preparation and retrofitting. CO_2 abatement cost and well-to-wake (WTW) emission reduction potential were estimated for the VLCC to provide a general indication relative to other solutions like energy efficiency initiatives and alternative fuels.

5.1 Newbuild integration

The VLCC's endurance was based on a Persian Gulf (PG)-Japan round trip (13,400nm, 41days) at a speed of 14.5 knots. We assumed that CO_2 would be discharged in PG for the VLCC case. Carbon reduction performance for the VLCC case is provided in Figure 7. For the LSFO fuel type, the OCC system increases CO_2 emissions by 42% due to the additional energy demand. In case of LSFO version and maximum carbon capture,

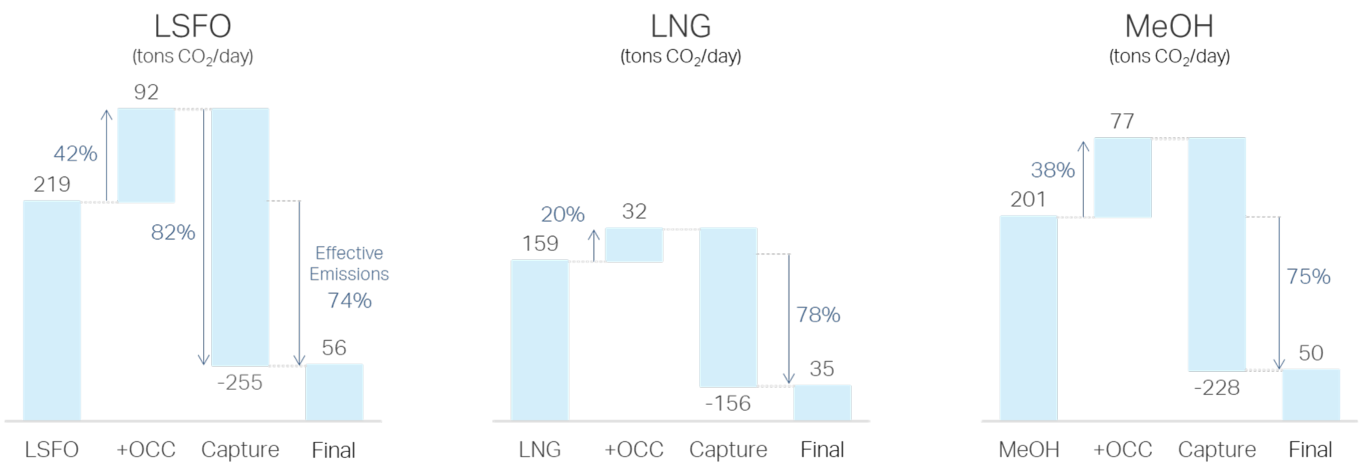


Figure 7: Carbon reduction calculation (VLCC).

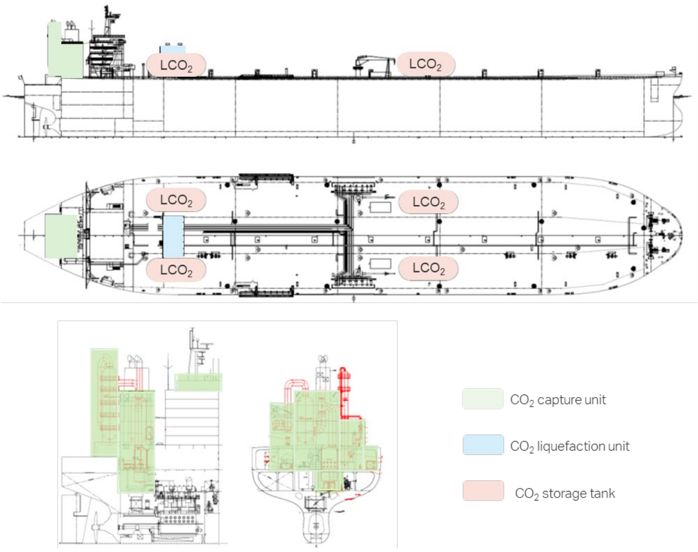


Figure 8: Vessel arrangement and major modification areas (VLCC).

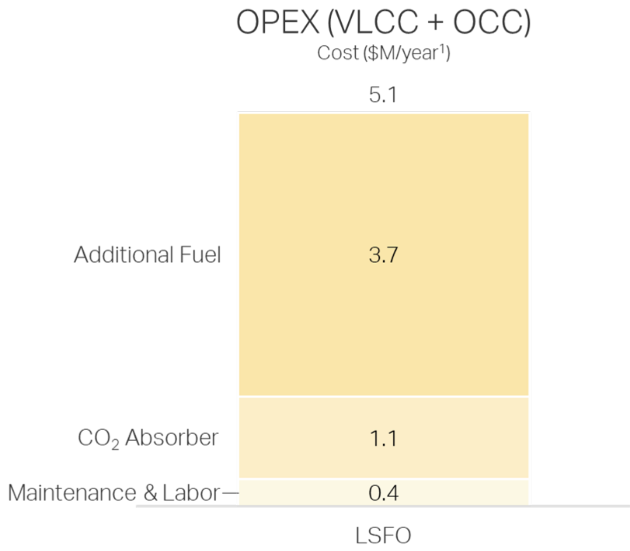


Figure 9: OPEX for VLCC+OCC.
[1]LSFO fuel price: $500/ton

about 55% of the additional energy is required for electricity (for circulation pump, liquefaction, etc.) and another 45% for steam (for separation of CO_2). With an 82% capture rate, the effective emission reduction compared to the base ship CO_2 emissions is 74%, which is like the MeOH version at 75% effective emission reduction. The LNG-fueled version can achieve 78% effective emission reduction due to a lower baseline CO_2 emissions and lower additional energy requirements.

Figure 8 shows the VLCC's vessel arrangement and the major modifications areas in the machinery, casing and deckhouse areas. For the VLCC, there is no cargo volume loss, however, the lightweight increase leads to a deadweight decrease of 3-4% (2,800-3,600 tons). There is a small impact on the vessel's bending moment that can be mitigated by adjusting loading conditions without strengthening the hull structure. As the CO_2 storage tanks are placed on deck, the bridge height needs to be increased 4-5 meters.

The CAPEX to install OCC for the VLCC ranges from 26% of the newbuild price for the LNG version to 42% of the newbuild price for the LSFO version. Additional OPEX ranges from $2.3 million for the LNG version to $5.2 million for the LSFO version.[3] Additional fuel for the LSFO version is $3.8 million or 73% of the total additional OPEX. See Figure 9 for an OPEX breakdown of the LSFO version.

5.2 Partial application

In addition to studying full application with maximum carbon capture rate, partial carbon capture was considered for the VLCC case. When incorporating partial capture, the tradeoff between additional energy needed and CAPEX should be considered (Figure 10). Up to a certain capture rate, excess steam from the main engine and auxiliary genset exhaust gas economizers (waste heat recovery) can be used, which reduces additional heat energy needed.

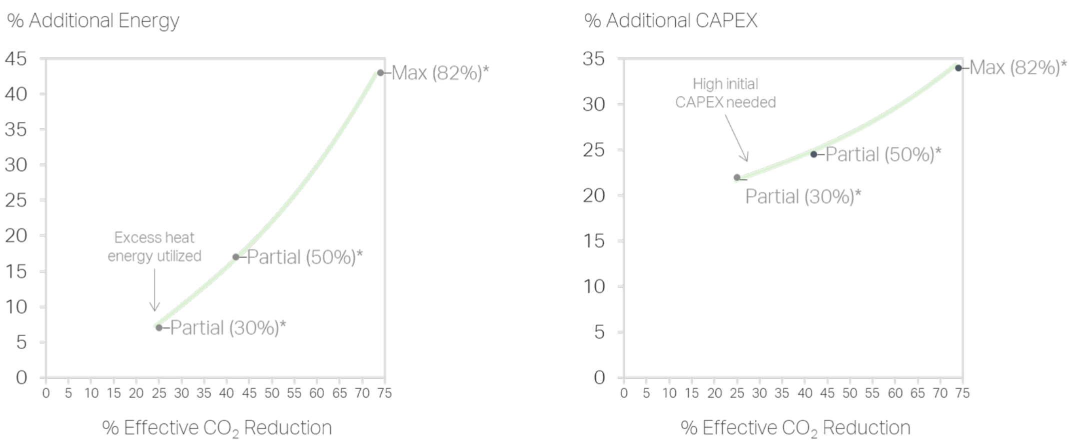


Figure 10: Partial carbon capture (VLCC).
Note: Graphs are indicative and show general trends; exact values will depend on type of engine, fuel, and temperature of exhaust gas.
*Percentages are carbon capture rate while the x-axis is showing the effective emissions after accounting for increased energy consumption.

[3] Assumes LSFO fuel price of $500/ton

Table 1: OCC newbuild preparation and conversion levels.

Preparation Level	Description
Level 0: Full retrofit	– No preparation/full retrofit
Level 1: Space allocated	– Enlarged casing for future installations – Supporting structure for capture unit and absorption chemical tanks
Level 2: Key Construction Elements Built	– Level 1 + liquefaction room, supporting structure for liquefaction unit and CO_2 tank support – Stability and longitudinal strength countermeasures – Wheelhouse raised – Mooring equipment rank up
Level 3: Yard Construction and Piping (except tank)	– Level 2 + all piping, main cabling and ventilation for new electric power plant and steam generating system – Retrofit scope: capture unit, liquefaction unit, tanks, unloading pumps/piping, absorption chemical tanks, sensors, etc.
Level 4: Fully Applied (Newbuild)	– Fully integrated in newbuild

Beyond this, the boiler is used to supply the needed heat energy, which increases the additional energy requirement for a given percentage of CO_2 reduction. While the additional energy for partial application can be minimized using excess heat, the initial CAPEX for partial application remains high. Achieving maximum capture rates can optimize cost per ton of CO_2 captured.

5.3 Newbuild preparation and retrofit

In this project, OCC case studies have been carried out mainly for newbuilds, however retrofitting existing fuel oil vessels and preparing newbuilds for retrofit was considered. Table 1 shows the different levels of preparation considered.

We conducted retrofit case studies for the following configurations:

- VLCC, LSFO, maximum capture (82%), no preparation (Level 0)
- VLCC, LSFO, maximum capture (82%), preparation Level 3
- VLCC, LSFO, half capture (50%), no preparation (Level 0)

When retrofitting OCC, one of the important items to consider is the increase in onboard power generation (gensets) capacity. As the increase in electric demand is large, gensets needs to be increased by both number and unit capacity.

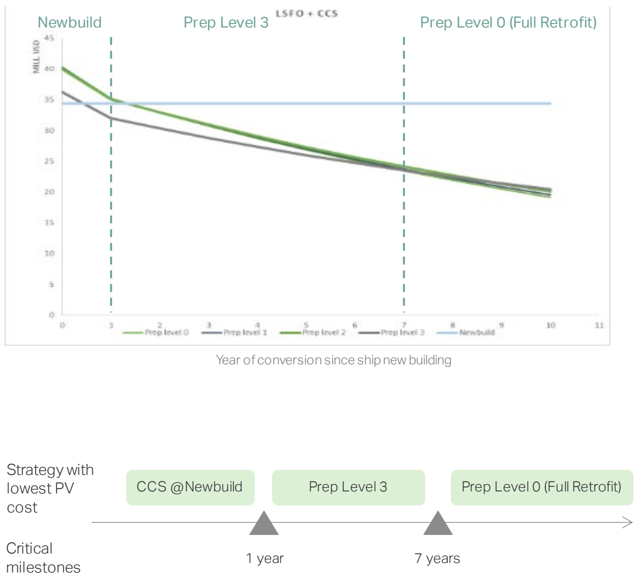


Figure 11: Present value cost for different newbuild preparation and retrofit levels (VLCC-LSFO case study).

In preparation Level 3, genset and boiler capacity are already increased at the newbuild phase. Hull structure is also prepared including an enlarged engine casing, increased height of the navigation bridge, and hull longitudinal strength margin.

Figure 11 shows present value cost for different newbuild preparation and retrofit levels for the maximum capture case. A full retrofit can be costly and require major modifications. A strategy involving some level of preparation can lead to lower present value cost. Although there is a small energy consumption penalty, preparation Level 3 with pre-installed major equipment including electric power and steam plant can save time and money later if the conversion timeline is within five to six years.

Table 2 shows the impact of retrofitting OCC with different capture rates for the VLCC. In case studies involving 50% CO_2 capture, there is no impact on longitudinal strength and visibility of the vessel. Since increasing the hull longitudinal strength would be difficult when retrofitting, it may be critical to prepare the hull, depending on the strength margin of the original design. Increasing the genset and boiler capacity is necessary for both cases, resulting in a lot of replacement work when retrofitting unprepared ships.

Table 2: Impact of partial carbon capture on retrofits.

Impact	Full application (CO_2 capture 82%)	Partial application (CO_2 capture 50%)	Notes
CO_2 tank	2,600 m^3 x 4 to be added on deck	2,600 m^3 x 2	
Hull longitudinal strength	Effect on max. bending moment 0 - 10% depending on original ship design	OK with original design	Increase of bending moment may be mitigated by adjusting loading condition without hull reinforcement
Stability	OK with original design	OK with original design	
Visibility	Increase of bridge height needed	OK with original design	
Genset	Need additional generator	NG with original design Need additional generator	Additional generator necessary for CO_2 capture system
Possibility to retrofit	Not feasible due to longitudinal strength, depending on original design	Possible with conversion in engine room and engine casing	

5.4 CO_2 abatement cost

We calculated CO_2 abatement costs using CO_2 reduction and financial estimates for the VLCC design with three fuel configurations (LSFO, LNG and MeOH). The VLCC is one of the best financial cases with lower abatement costs relative to the other cases due to its large size and no assumed cargo loss. While there was a decrease in cargo deadweight, there was no cargo volume loss. The other vessel types would have to consider potential lost revenue associated with cargo loss. A summary of the calculation is provided in Table 3. A tank-to-wake (TTW) abatement cost ($/ton$CO_2$) was calculated using the total CO_2 avoidance in tons CO_2/year. The financials were translated into a $M/year value assuming a 20-year lifetime and other financial assumptions related to interest rates, debt finance and cost of equity. For the VLCC, the TTW abatement cost ranges from $180-260/ton$CO_2$.

The TTW abatement cost considers the total CO_2 avoidance, however, additional emissions related to the additional energy consumption should be deducted to provide a more accurate abatement cost estimate. A corrected WTW CO_2 avoidance

Table 3: CO_2 abatement cost calculation (VLCC).

[1]Assumptions: Vessel Lifetime: 20 years, Interest Rate: 5%, Debt Finance: 60%, Cost of Equity: 10%, LSFO Price: $500/ton, LNG Price: $400/ton, CO2 Storage Cost: $25/ton, Sailing 250 days/year

[2]CO_2 avoidance is reduced by the well-to-tank, 100-year GWP, emissions associated with the additional energy consumption (LSFO: 13.2 gCO_2/MJ, LNG: 19.6 gCO_2eq/MJ; LCV for LSFO: 41.2 MJ/kg, LNG: 48 MJ/kg) and onboard methane slip from diesel generators (3.1%)

[3]Additional fuel consumption for methanol vessel assumes genset using fuel oil

	LSFO	LNG	Methanol
Total CO_2 avoidance (tons/year)	40,700	31,300	37,700[3]
CAPEX ($M/year)	4.4	3.2	3.9
OPEX ($M/year)	5.0	1.8	3.9
CO_2 Storage ($M/year)	1.0	0.8	0.9
Total Cost ($M/year)	10.4	5.8	8.8
Abatement Cost – TTW ($/ton CO_2)[1]	**250-260**	**180-190**	**230-240**
Corrected CO_2 avoidance (tons/year)[2]	36,700	26,100	34,400
Abatement Cost – WTW ($/ton CO_2)	**280-290**	**220-230**	**250-260**

value was calculated by deducting the WTW emissions and onboard methane slip (for LNG) associated with the additional energy consumption to power the OCC system. This led to an increased abatement cost ranging from $220-290/ton$CO_2$.

The LNG and MeOH CO_2 abatement costs in Table 3 do not include any additional costs to design and build those vessels relative to a LSFO vessel. The CO_2 abatement costs only consider the additional CAPEX and OPEX of adding OCC to each vessel type. Any assessment or comparison of adding OCC versus selecting an LSFO alternative like LNG or methanol should consider additional vessel costs relative to an LSFO vessel.

5.5 OCC emission reduction potential

In addition to determining the CO_2 abatement cost range, the true emission reduction potential of the OCC system is important for determining the applicability of the solution. For example, can OCC systems be considered equivalent to using alternative fuels? To properly compare the emission reduction of onboard technology such as OCC to alternative fuels, the WTW emission reduction was calculated (Table 4).

While onboard CO_2 capture rates can be high (up to 82% in our case), this does not directly translate to actual WTW emission reductions. Emissions associated with additional energy consumption reduces emission reduction from 82% to 74-78%. The WTW emission reduction potential is between 55-60% mainly due to well-to-tank emissions increasing the initial baseline that then the captured CO_2 is compared to. Additional CO_2 emissions will occur during the transportation and storage of the captured CO_2, which is not currently included in our calculations. Transportation emissions are related to potential boil off during transportation and GHG emissions from the transportation itself. Storage emissions are related to CO_2 injection at the storage site.

Table 4: OCC emission reduction potential.

[1]Relative to WTW LSFO emissions, the percent reduction onboard carbon capture can provide, 100-year GWP, CO_2-eq includes methane, LSFO: 15.9 gCO_2/MJ, LNG: 20.48 gCO_2eq/MJ (Source:

	LSFO	LNG
Capture ratio (%)	82	82
Effective reduction / avoidance (%)	74	78
WTW emission reduction relative to LSFO (%)[1]	55-60	55-60

While an emission reduction of 55-60% is not comparable to the use of an alternative fuel with near-zero emissions, it is still significant and could contribute to reducing emission intensity of existing fuel oil vessels as a bridging technology. This is especially the case in scenarios where the build-out of renewable energy and/or sectoral competition is too high for shipping to get access to near-term low carbon alternative fuels. In this scenario, OCC and subsequent storage may offer a commercially less complex option. The long-term use of OCC with low-carbon fuels like electro or bio-methanol requires further study to understand emission reduction potential and relevant scenarios as part of a methanization cycle.

6 Conclusions

This work provides a general indication for both abatement cost and emission reduction potential that can be used to assess OCC's business case. For a VLCC newbuild, the best case studied, CO_2 abatement cost ranges from $220-290/ton$CO_2$ with an WTW emission reduction potential of 55-60%. Based on the case studies completed, we have also concluded that:

- OCC with chemical absorption is technically feasible and expected to reach commercial availability by 2030,
- Additional OCC energy requirements lead to higher total fuel consumption (up to a 45% increase),
- Potential application of OCC shows the most promise for newbuilds as retrofits are costly and can require major modifications,
- Partial carbon capture typically leads to higher CO_2 abatement costs due to high initial CAPEX, and
- Large tankers have the best business cases while small bulk carriers have the most challenges.

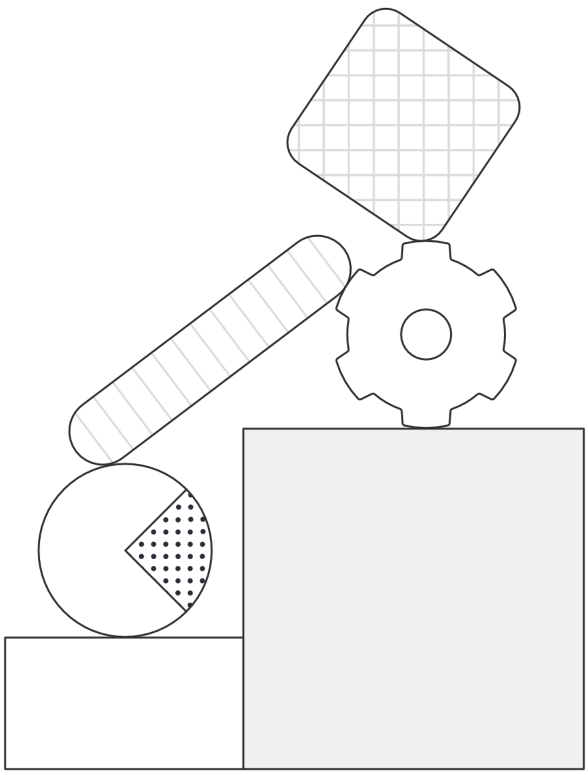
OCC CO_2 abatement costs are currently expected to be high, but emission reduction potential can be significant. Based on the potential role OCC could play in the mid-term to reduce emission intensity of existing fossil-fueled vessels (bridging technology), the technology should be further developed and considered in parallel and in combination with alternative fuels.

While the presented case studies provide an initial understanding of OCC's potential, it is an incomplete picture that requires further analysis and development. This study only considered the amine-based absorption OCC technology. However, there are other technologies that are less developed, but can potentially offer different opportunities such as higher capture rates and lower energy requirements.

Further technology development focused on mitigating main risks and reducing overall cost and energy demand for the amine-based absorption OCC technology can improve the business case by maximizing carbon capture rates and minimizing CAPEX and OPEX. A use case considering heavy fuel oil with scrubbers on existing vessels and the potential need for pre-treatment should also be studied. The potential of pre-combustion capture from carbon-based fuels using reformers in combination with fuel cells, for example, should be also be studied further.

Identifying potential business models that can utilize the carbon captured onboard vessels should be studied further well as the possibility for permanent storage. As for the rest of the green transition technologies, OCC relies on carbon tax credits and an option for selling captured CO_2 on the open market. The quality of the CO_2 captured onboard and utilization including discharge, infrastructure development and use of green fuels as part of methanation cycle should also be studied.

The MMMCZCS has recently initiated a parallel research project to assemble market knowledge of CO_2 storage. The focus of this project is on the storage and logistics costs for various types of storage, the near-term potential and limitations on global storage capacities, and the suitability of geographies for blue ammonia production. The increasing demand for CO_2 storage and associated CO_2 transportation is leading to the creation of a new shipping segment focused on CO_2 transport. While the development of CO_2 shipping is largely independent of OCC, it is connected as port infrastructure and storage of CO_2 captured onboard vessels can leverage the expansion of CO_2 transport and shipping.



Appendix

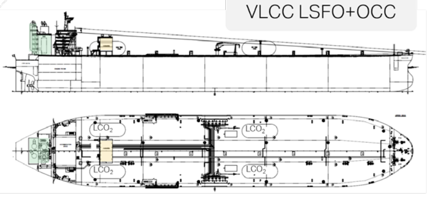
Case study snapshots (Mitsubishi Heavy Industries)

Case study: VLCC

CO_2 capture unit
CO_2 liquefaction unit

MITSUBISHI HEAVY INDUSTRIES, LTD.

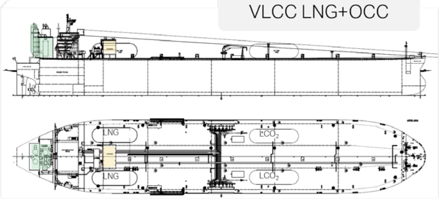
VLCC LSFO+OCC



PG-Japan round trip
FO tank 4,470m³
LCO_2 Tank 2,575m³ x 4 tk

Effect on main Hull
Bridge height 3.5m
Longi. Strength 5%

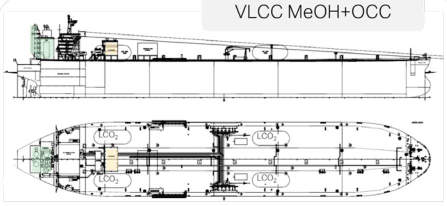
VLCC LNG+OCC



PG-Japan round trip
LNG tank 3,550m³ x 2tk
LCO_2 Tank 3,150m³ x 2 tk

Effect on main Hull
Bridge height 4.5m
Longi. Strength 5%

VLCC MeOH+OCC



PG-Japan round trip
MeOH tank 7,050m³
LCO_2 Tank 2,275m³ x 4 tk

Effect on main Hull
Bridge height 3.5m
Longi. Strength 5%

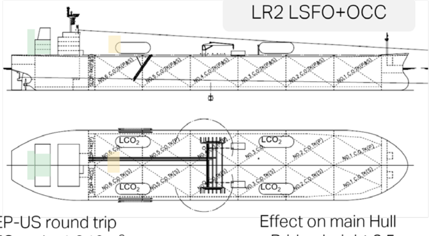
	LSFO+OCC	LNG+OCC	MeOH+OCC
Main Engine	7G80ME-C9.5 17,120 kW @14.5kt	7G80ME-C9.5-GI 17,120 kW @14.5kt	7G80ME-C9.5-LGIM 17,120 kW @14.5kt
Extra Energy for CC	+42%	+20%	+38%
Captured CO_2	255 ton/day	156 ton/day	228 ton/day
CO_2 Capture CO_2 Reduction	82% (including additional CO_2 by CC) 74% (Reduced from LFSO w/o CC)	82% 78% (from LNG w/o CC)	82% 75% (from MeOH w/o CC)
Cargo Loss by CC	Volume: None Cargo wt: -10,700 ton (-3.6%)	Volume: None Cargo wt: -7,700 ton (-2.6%)	Volume: None Cargo wt: -7,500 ton (-2.5%)
Additional CAPEX for CC	42%	26%	33%

Case study: LR2 Tanker

CO_2 capture unit
CO_2 liquefaction unit

MITSUBISHI HEAVY INDUSTRIES, LTD.

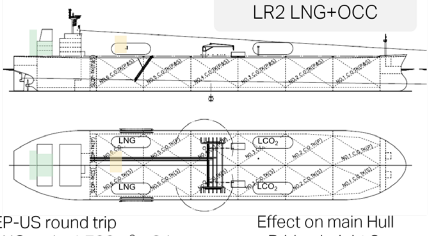
LR2 LSFO+OCC



EP-US round trip
FO tank 1,340m³
LCO_2 Tank 785m³ x 4 tk

Effect on main Hull
Bridge height 2.5m
Longi. Strength 5%

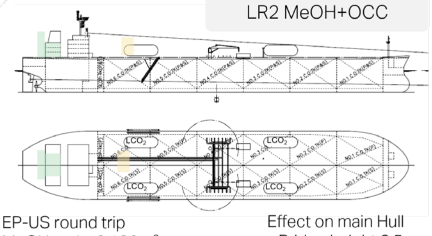
LR2 LNG+OCC



EP-US round trip
LNG tank 1,790m³ x 2tk
LCO_2 Tank 1,020m³ x 2 tk

Effect on main Hull
Bridge height 3 m
Longi. Strength 5%

LR2 MeOH+OCC

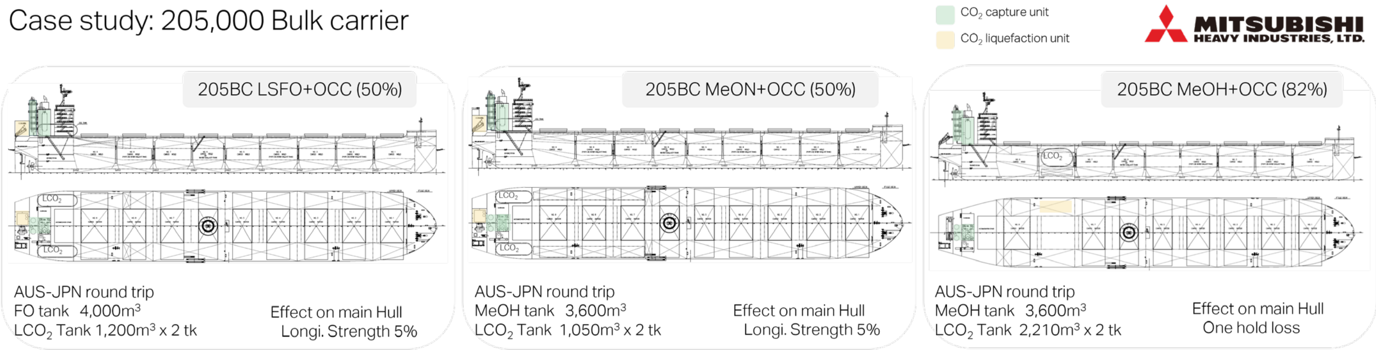


EP-US round trip
MeOH tank 2,180m³
LCO_2 Tank 690m³ x 4 tk

Effect on main Hull
Bridge height 2.5m
Longi. Strength 5%

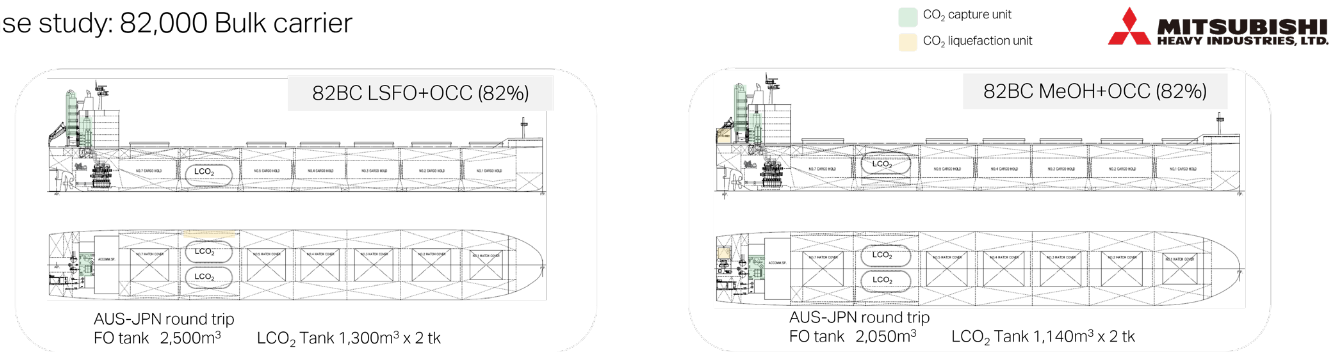
	LSFO+OCC	LNG+OCC	MeOH+OCC
Main Engine	6G60ME-C9.5 8,680 kW @13.5kt	6G60ME-C9.5-GI 8,680 kW @13.5kt	6G60ME-C9.5-LGIM 8,680 kW @13.5kt
Extra Energy for CC	+41%	+27%	+35%
Captured CO_2	133 ton/day	88 ton/day	116 ton/day
CO_2 Capture CO_2 Reduction	82% (including additional CO_2 by CC) 75% (Reduced from LFSO w/o CC)	82% 77% (from LNG w/o CC)	82% 76% (from MeOH w/o CC)
Cargo Loss by CC	Volume: None Cargo wt: -3,600 ton (-3.5%)	Volume: None Cargo wt: -2,900 ton (-2.8%)	Volume: None Cargo wt: -2,800 ton (-2.8%)
Additional CAPEX for CC	47%	36%	41%

Case study: 205,000 Bulk carrier



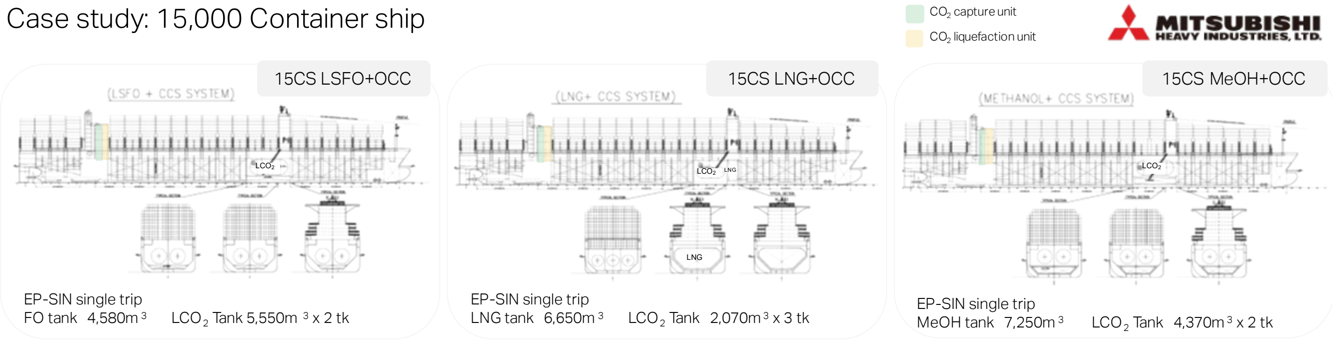
	LSFO+OCC (50%)	MeOH+OCC (50%)	MeOH+OCC (82%)
Main Engine	6G70ME-C9.5 11,035 kW @13.5kt	6G70ME-C9.5-LGIM 11,035 kW @13.5kt	6G70ME-C9.5-LGIM 11,035 kW @13.5kt
Extra Energy for CC	+16%	+11%	+38%
Captured CO_2	82 ton/day	72 ton/day	144 ton/day
CO_2 Capture CO_2 Reduction	51% (including additional CO_2 by CC) 43% (Reduced from LFSO w/o CC)	51% 45% (from LNG w/o CC)	82% 75% (from MeOH w/o CC)
Cargo Loss by CC	Volume: None Cargo wt: -1,500 ton (-1.0%)	Volume: None Cargo wt: -2,400 ton (-1.1%)	Volume: -24,000 m³ (-10.7%) Cargo wt: -4,100 ton (-2.0%)
Additional CAPEX for CC	41%	36%	43%

Case study: 82,000 Bulk carrier



	LSFO+OCC (82%)	MeOH+OCC (82%)
Main Engine	6S60ME-C10.6 6,059 kW @13.5kt	6S60ME-C10.6-LGIM 6,059 kW @13.5kt
Extra Energy for CC	+40%	+31%
Captured CO_2	91 ton/day	77 ton/day
CO_2 Capture CO_2 Reduction	82% (including additional CO_2 by CC) 74% (Reduced from LFSO w/o CC)	82% 76% (from MeOH w/o CC)
Cargo Loss by CC	Volume: -15,300 m³ (-15.7%) Cargo wt: -1,500 ton (-1.8%)	Volume: -15,300 m³ (-15.7%) Cargo wt: -2,300 ton (-2.8%)
Additional CAPEX for CC	70%	55%

Case study: 15,000 Container ship

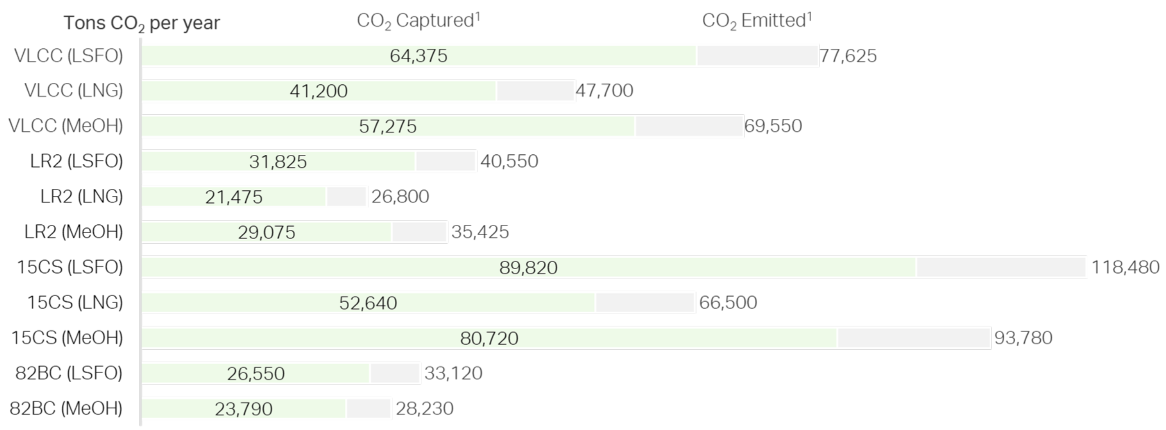


	LSFO+OCC	LNG+OCC	MeOH+OCC
Main Engine	8G95ME-C10.5 31,000 kW @19kt	8G95ME-C10.5-GI 31,480 kW @19kt	8G95ME-C10.5-LGIM 31,120 kW @19kt
Extra Energy for CC	+45%	+18%	+28%
Captured CO_2	486 ton/day	273 ton/day	384 ton/day
CO_2 Capture CO_2 Reduction	82% (including additional CO_2 by CC) 74% (Reduced from LFSO w/o CC)	82% 79% (from LNG w/o CC)	82% 77% (from MeOH w/o CC)
Cargo Loss by CC	Slot: -1,200 TEU (-8.0%) Cargo wt: -9,900 ton (-7.4%)	Slot: -1,100 TEU (-7.0%) Cargo wt: -6,800 ton (-5.1%)	Slot: -1,200 TEU (-8.0%) Cargo wt: -7,800 ton (-5.8%)
Additional CAPEX for CC	38%	27%	32%

Newbuild ship integration considerations

	Tankers (82%)	Bulk carriers (50%)	Bulk carriers (82%)	Container ships (82%)
Cargo loss	No volume loss Cargo weight loss 3-4% (2,800-3,600 tons)	No capacity loss	One hold loss	Slot loss 8% (1200 TEU for 15k)
Longitudinal strength [1]	Some Impact (5%[1]) depending on design	Some Impact (5%[1]) depending on design	CO_2 tank located in cargo hold	Significant impact with CO_2 tank for EP-FE roundtrip No impact for single trip
Stability	No impact	No impact	No impact	Same as longitudinal strength
Visibility	Bridge height to be increased by 4-5m	No impact	No impact	No impact
Assumptions	VLCC Endurance: 13,000-14,000 nm Speed: 14.5 kt (≈80% MCR) LR2 Endurance: 20,500-20,600 nm Speed: 13.5 kt (≈70% MCR)		Endurance: 23,000-25,000 nm Speed: 13.5 kt (≈63-70% MCR)	Endurance: 8,300 nm (Single trip Rotterdam to Singapore) Speed: 19 kt (≈70% MCR)

Annual CO_2 emissions and captured CO_2



1 Assumed sailing days per year – Tankers: 250 days, Bulk: 300 days, Container: 200 days