Retrofit of an 82,000 DWT bulk carrier for methanol dual-fuel capability

A technical and economic analysis

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

Executive summary

Methanol as a low-carbon marine fuel offers a decarbonization pathway for shipping operators. In particular, methanol's specific molecular properties allow for conversion of existing assets to methanol-powered propulsion. However, there are many technical and economic factors to consider when assessing how and when to undertake such a retrofit, including fuel storage, safety assessments, and financial feasibility.

To help illuminate these considerations, we undertook a project examining the technical and economic feasibility of retrofitting an 82,000-deadweight tonnage (DWT) bulk carrier for methanol dual-fuel operation. Our primary objective was to delineate the opportunities and challenges associated with converting medium-sized bulk carriers to methanol capability. We focused on this vessel segment primarily because most bulk carriers currently on order can only operate on fuel oil, implying that their decarbonized operation will require retrofitting to alternative fuels.

This report describes the retrofit design package developed in our study. We elaborate on the specific design objectives and requirements essential for the retrofit. We developed and checked an array of technical solutions for the retrofit options and selected the most viable one considering the vessel's relevant design and operational parameters.

The report also summarizes the results of the full hazard identification (HAZID) to address the hazards and safety considerations integral to the design, ensuring adherence to regulatory standards and safety protocols.

Lastly, we evaluated the economic feasibility of retrofitting bulk carriers. This evaluation includes a thorough analysis of the economic implications of such conversions. At the same time, this analysis demonstrates the retrofit's potential benefits for emissions reductions and environmental compliance.

The main takeaways from our study are:

- Retrofitting existing assets to methanol is technically feasible, even though available solutions for bulk carriers are limited

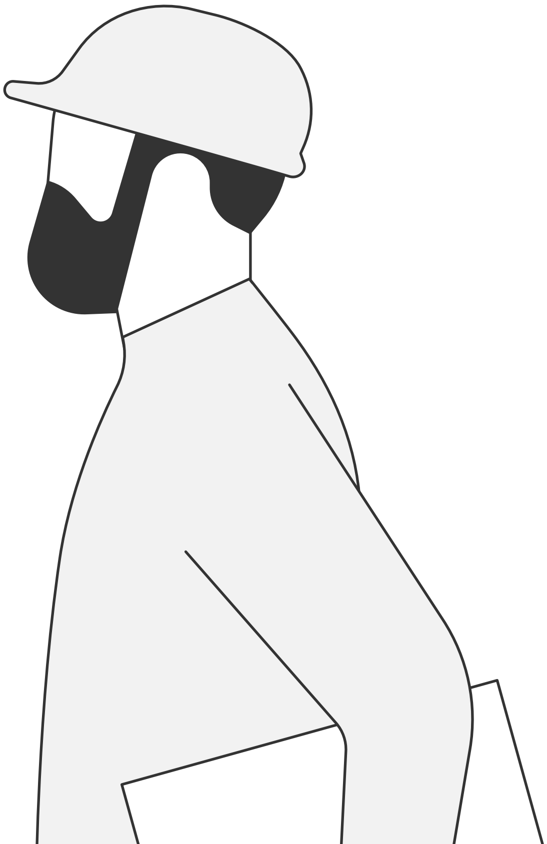
- We did not identify any critical safety risks associated with the retrofit concept

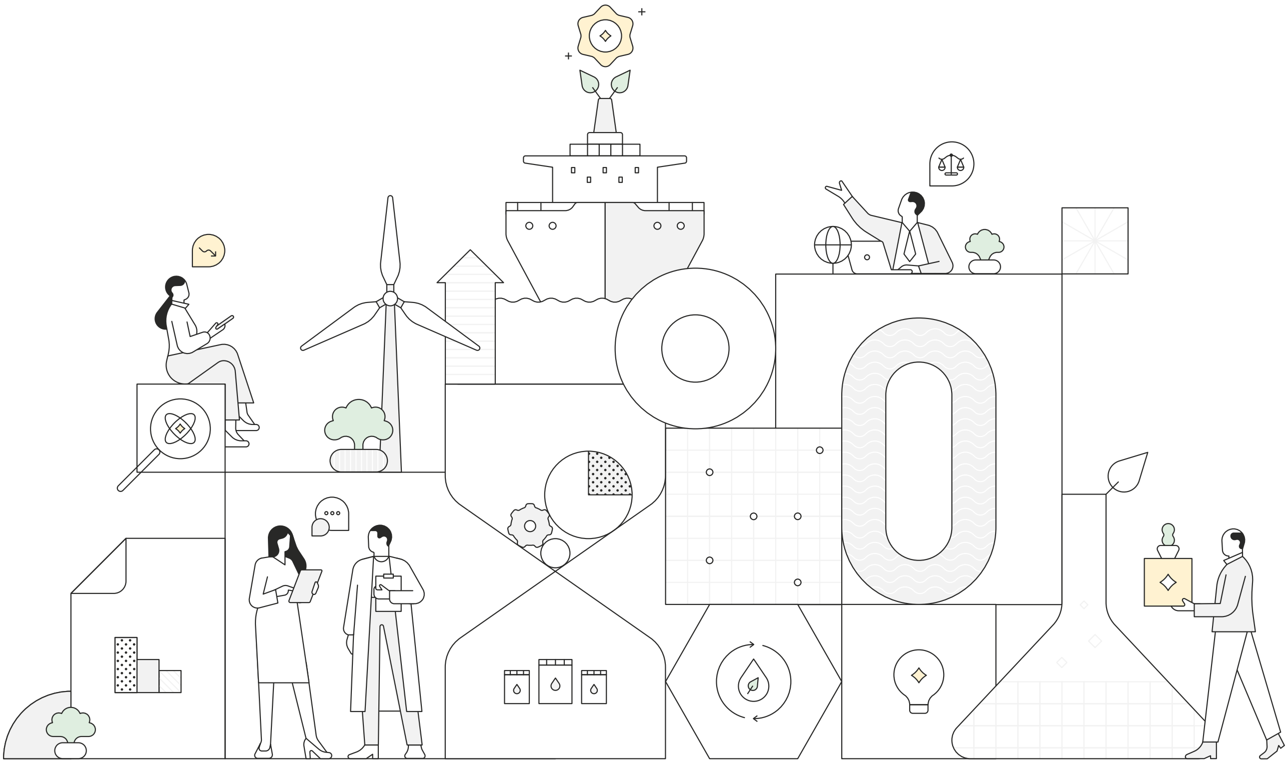
- Defining and executing as much of the retrofit work as possible offline limits the impact of off-hire cost

- Conversion to methanol capability comes with certain limitations on the deadweight and cargo carrying capacity, which are considered within our cost analysis

- An economic analysis based on our calculations and assumptions suggests that the business case for this retrofit hinges on the price of sustainable methanol

This report is aimed at shipowners, ship operators, shipyards, equipment manufacturers, and ship designers. It serves as an illustrative example of a retrofit study on an existing standard design and as inspiration for understanding the challenges and opportunities relevant to methanol retrofits, particularly for medium-sized bulk carriers.





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01 Introduction

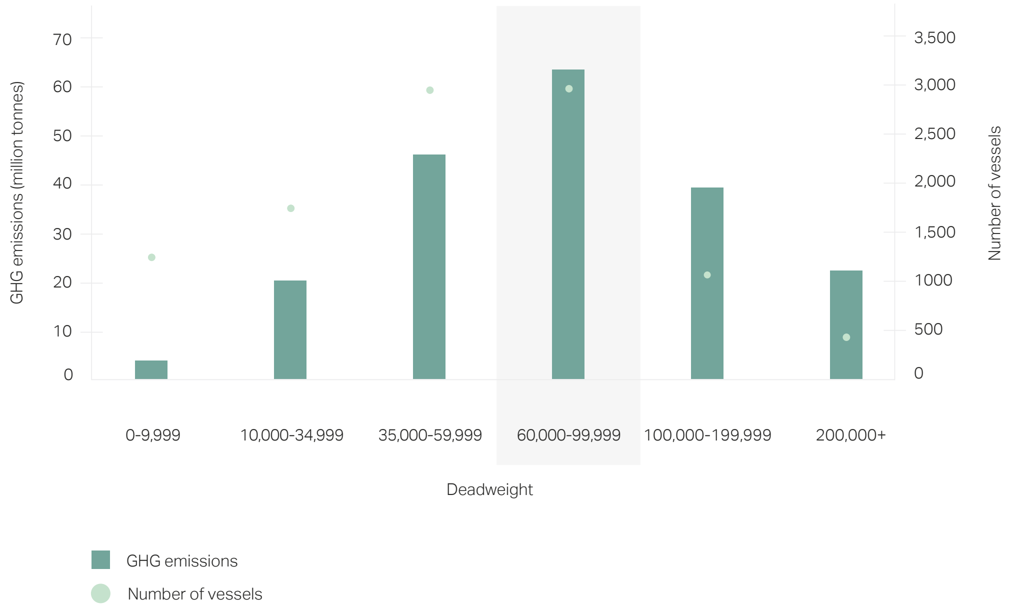
The International Maritime Organization (IMO) aims to achieve net-zero greenhouse gas (GHG) emissions by 2050.[1] While newbuilding vessels are an important piece of the puzzle, retrofitting existing ships to operate on alternative fuels will also play a significant role in reducing GHG emissions,[2] especially considering the IMO's current ambitions.

Bulk carriers account for 14% of the global merchant vessel fleet, with medium-sized vessels (60,000-99,000 DWT) comprising approximately 28% of the bulk carrier fleet. The Kamsarmax vessel is one of the largest vessels within this medium-sized category. In 2018, this category was responsible for about 63 million tonnes of GHG emissions (Figure 1), representing 6% of total fleet emissions. Medium-sized bulk carriers, specifically Kamsarmax vessels, are also identified as a significant source of GHG emissions in the IMO's Fourth GHG Study.[3]

According to Clarksons Research,[4] the Kamsarmax fleet has an average age of 10.3 years, compared to around 12 years for bulk carriers overall. Furthermore, 99.8% of the existing fleet consists of conventional single-fueled vessels, while for newbuilding vessels, 94.8% will be conventionally fueled.[5]

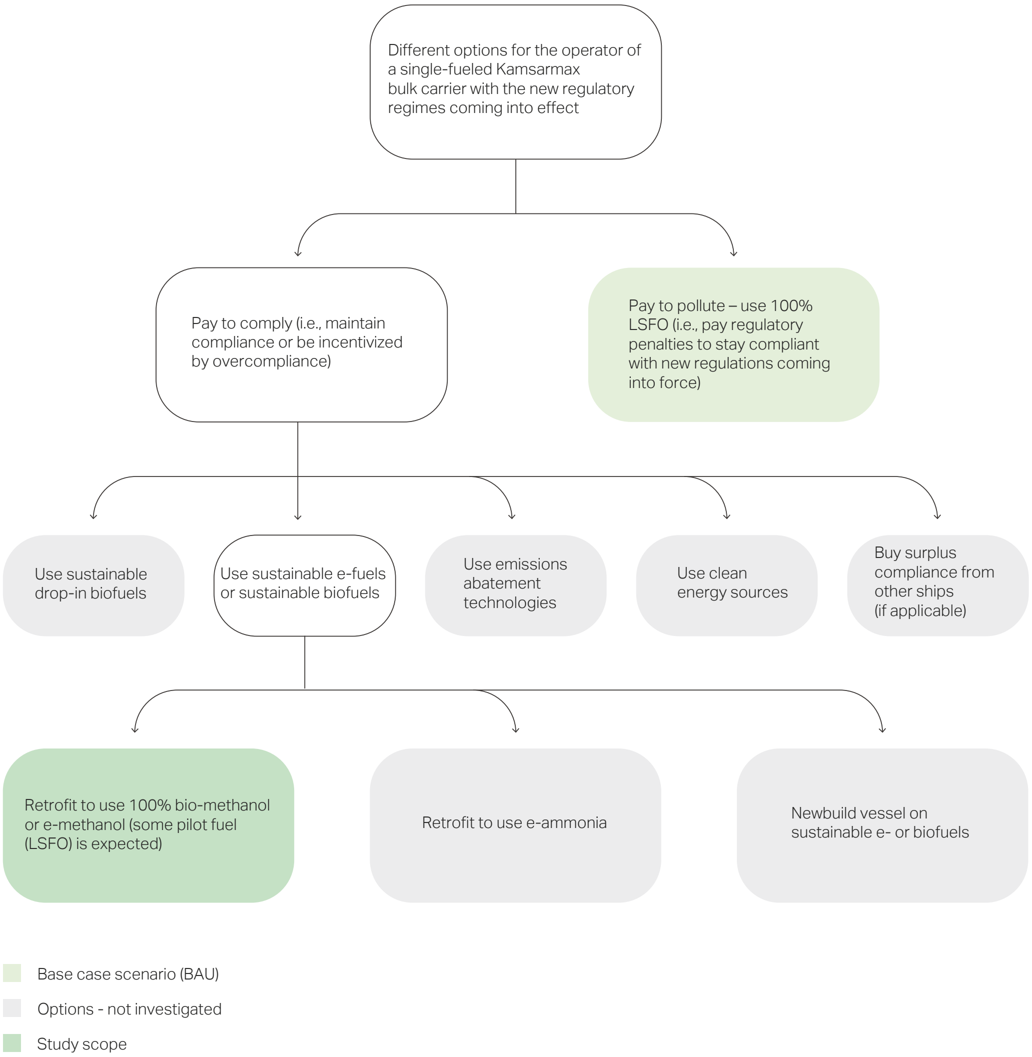
Figure 2 shows the different options that owners can consider when decarbonizing bulk carriers.

Figure 1: GHG emissions and number of vessels in the bulk carrier fleet, based on the IMO's Fourth GHG study.[3]



GHG = green house gas

Figure 2: Different options for decarbonizing Kamsarmax bulk carriers.



It is important to recognize that bulk carriers predominantly operate within the tramp sector. Most of these vessels do not operate according to a set schedule and are expected to operate globally, calling at different ports worldwide.

In the future, bulk carrier operators will face the dual challenge of operating in a multi-fuel reality, while finding green fuels that will enable them to meet decarbonization targets.

Most bulk carrier vessels currently in service are powered by conventional fuel.[3] Efforts to decarbonize these existing vessels will require consideration of options such as drop-in biofuels or retrofitting vessels to enable the use of alternative fuels. This study focuses on the latter option, specifically retrofitting for methanol capability.

Figure 3 illustrates the benefits of considering methanol as a retrofit candidate (see also MMMCZCS 2024).[2]

BAU = business as usual, LSFO = low-sulfur fuel oil

Figure 3: Benefits of methanol retrofit.

- Retrofitting internal combustion engines may offer a practical, cost-effective pathway to fleet decarbonization.[6]
- Mature dual-fuel engine technology.
- Retrofits can help ensure compliance with evolving environmental regulations and standards.

- Methanol is a liquid at ambient temperature and pressure.
- The simplified onboard storage and handling make this fuel a practical choice for retrofitting.[2]

- Methanol produced from renewables, such as biomass, or via carbon capture and utilization reduces the shipping industry's carbon footprint.[7]

- Methanol is biodegradable and less harmful to marine life than conventional marine fuels, making potential spills less hazardous.[8]

1.1 Overview of this report

This report presents a technical and economic study of an existing bulk carrier, examining the major design considerations for retrofits and demonstrating technical feasibility. It serves as a case study for shipyards and designers interested in methanol retrofit designs, offering practical examples of challenges and solutions. Additionally, it provides insights for shipowners and operators on the operational aspects of retrofit projects, including integration beyond the conceptual phase.

Below is a brief overview of the main sections of this report.

Section 3 describes the general design objectives and requirements for this study. These include endurance requirements, vessel particulars, and methanol fuel hazards.

Section 4 examines various tank arrangements to find the most optimal in terms of volume, endurance, and technical acceptance (structural and stability criteria). Design reviews identified the most suitable arrangement for the purposes of this study, considering cargo capacity loss, potential operational restrictions, and compliance with vessel rule requirements.

Section 5 assesses the installation approach for the methanol storage tank, focusing on yard handling capability and coating requirements. It also examines the conversion time required.

Section 6 shares the results of a thorough HAZID review, which assessed hazards and mitigation actions. The final design received Approval in Principle (AiP) from ClassNK, confirming its robustness and safety compliance. A retrofit design package has been developed, based on a representative Kamsarmax design, with widespread applicability across the fleet. This approach has the potential to accelerate the fleet's transition to low-emission alternative fuels.

Finally, *Section 7* presents the results of an economic analysis regarding the overall opportunities and challenges of retrofitting an existing asset for methanol capability.

02 About this project

MMMCZCS and Tsuneishi led this project, and MMMCZCS prepared the report in collaboration with our partners. Tsuneishi developed the detailed project concept design, Everllence supported with engine design considerations, ClassNK facilitated the HAZID and reviewed the AiP package while providing statutory guidance, Cargill provided operational insights throughout the project, and the Danish Maritime Authority contributed to the safety discussions in the HAZID.

DANISH MARITIME AUTHORITY

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03 Design objectives and requirements

The project assessed various tank arrangement options. The primary objective was to increase methanol tank capacity and endurance for typical trade routes for this vessel size, while minimizing cargo loss. Our aim was to meet an acceptable level of vessel specification post-conversion, including deadweight, cargo hold capacity, operation, and endurance.

The trading routes and associated endurance significantly influence the sizing of the methanol storage tank, as well as potential locations for the tank within the vessel's general arrangement. For this project, we have considered all typical routes that Kamsarmax may be trading on. Table 1 outlines the routes considered in this feasibility assessment.

It is important to avoid altering the allowable longitudinal strength. While it may be feasible to add construction components to enhance the longitudinal strength, such modifications could be classified as a "major conversion." In this scenario, the vessel must adhere to the latest rules and regulations at the time of conversion, necessitating a comprehensive design review.

Our process also prioritized minimizing the retrofit time by employing a simplified design, thereby reducing the vessel's time out of charter.

Table 1: Representative routes for Kamsarmax bulk carriers.

Endurance	Representative routes (Baltic Kamsarmax)	Methanol tank capacity based on a service speed of 14.3 knots
Short (5,000 NM)	P1 (Atlantic Round) one way P3 (Pacific Round) one way	Small (1,100~1,200 m³)
Medium (10,000 NM)	P1 (Atlantic Round) one trip P3 (Pacific Round) one trip	Medium (2,300~2,400 m³)
Long (16,000 NM or more)	P2 (Fronthaul) one trip P4 (Backhaul) one trip P6 (East Coast South America Round) one way P6 (East Coast South America Round) one trip with touch bunker at South Africa	Large (3,600~3,700 m³)

NM = nautical miles

3.1 Vessel considered for retrofit case study

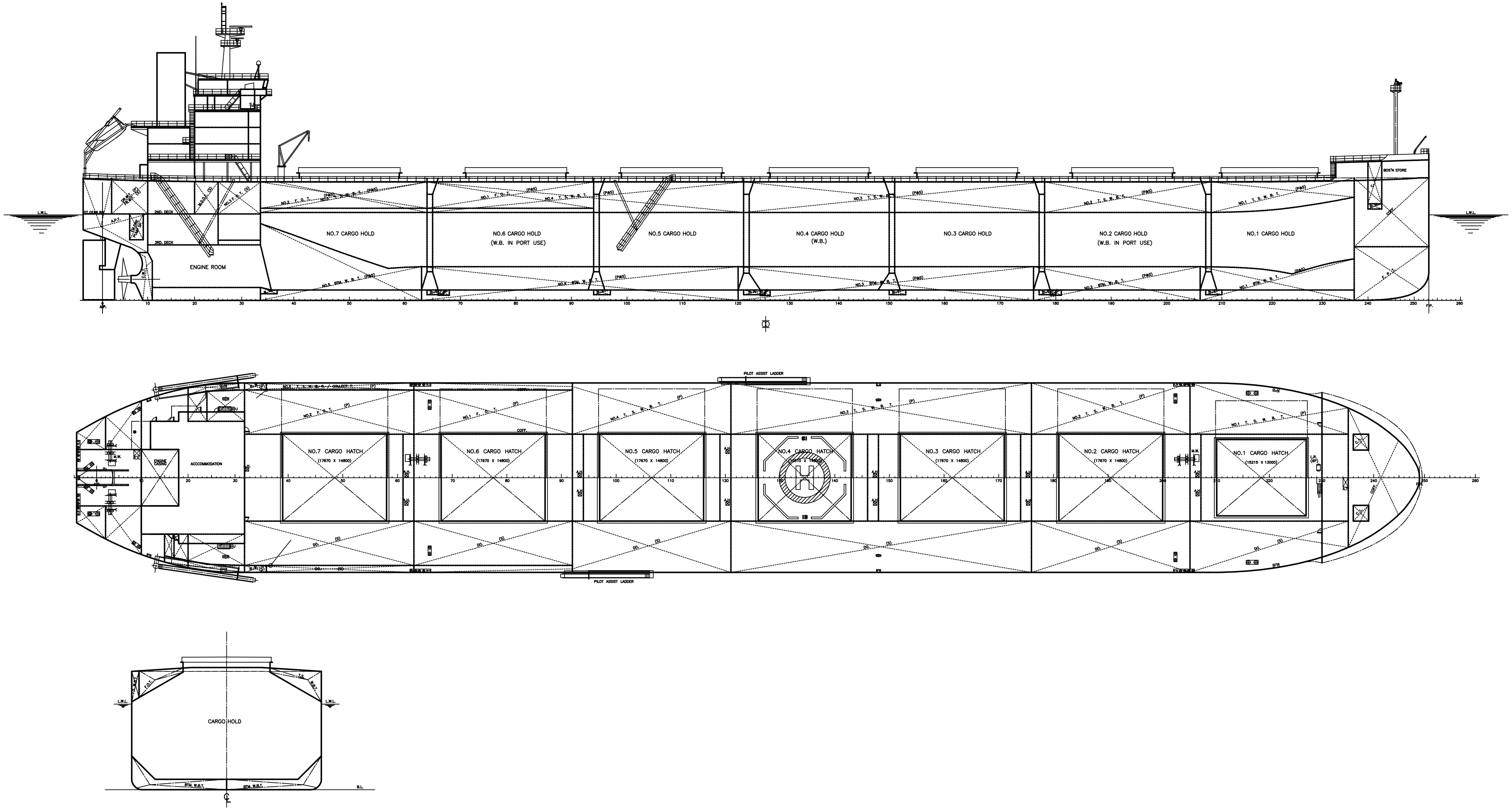
We selected an 82,000 DWT bulk carrier (82BC) for the methanol retrofit study. Table 2 presents the vessel's principal particulars, and Figure 4 shows the profile, plan, and section view.

Table 2: Principal particulars for the medium-sized bulk carrier selected for the methanol retrofit.

Principal particulars		Note
Delivered year	2020	Target vessels should be relatively young (5–10 years of remaining lifetime) to render the retrofit viable over the lifecycle
LOA	229 m	
Breadth	32.26 m	
Depth	20.15 m	
Draft (scantling)	14.55 m	
Deadweight	82,300 MT	
Service speed	14.3 knots	
Endurance	~ 28,600 NM	Based on main engine consumption only
Cargo type	Grain, coal, iron ore, hot coil	
No. of cargo holds	7	
Total cargo hold volume	98,000 m^3	
Cargo gear	Not applied	
Type of hatch cover	Side rolling	
Main propulsion	Everllence B&W 6S60ME-C10.5 x 1set	
SO_x scrubber	Not applied	
Main fuel	LSFO	

LOA = length overall, MT = metric tonnes, NM = nautical miles, LSFO = low-sulfur fuel oil

Figure 4: Profile, plan, and section view of existing vessel.



3.2 Methanol fuel hazards for design considerations

Table 3 provides guidance on the main properties of methanol as fuel which have been considered in the design process.

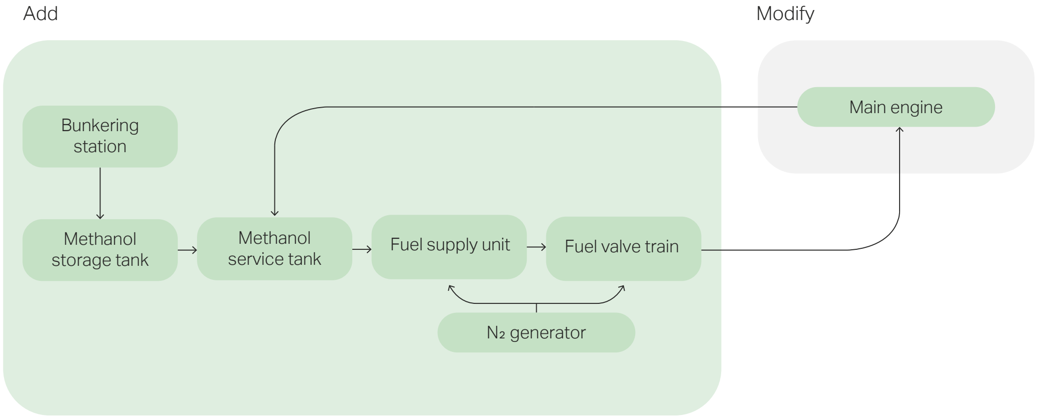
Table 3: Hazards of methanol as a fuel.[9]

Toxicity	- Methanol primarily enters the body through inhalation, skin contact, and eye contact. - Methanol is equally toxic, no matter how it enters the body.
Exposure control	- Gas detectors are necessary. Detecting vapors through odors is not reliable. - Permissible exposure limit – time-weighted-average (PEL-TWA): 200 ppm, 8 hours/day, 40 hours/week.[10] - Immediately dangerous to life or health limit (IDLH): 6,000 ppm.[11]
Fire	- Lower explosive limit: 6% at 12–41°C. - Upper explosive limit: 36.5% at 12–41°C. - A methanol fire is difficult to see. - The vapor is near neutral in buoyancy and follows air movements.
Corrosion	- Corrosion should be taken into account for equipment built with copper alloys, galvanized steel, titanium, aluminum alloy components, and certain plastics and composites.

04 Retrofit technical feasibility study

A retrofitted methanol fuel system is identical to the system installed on a newbuild. Figure 5 shows key components of the fuel system: methanol storage tanks, service tank, fuel supply unit, and fuel valve train (FVT). Additional systems cover ventilation, drainage (including a methanol drainage tank), nitrogen (N_2) supply, firefighting, and emergency shutdowns.

Figure 5: General methanol flow in the fuel supply system for a retrofit.



N_2 = nitrogen

4.1 Options for fuel storage tank arrangement and impact assessment

Installing a methanol fuel tank is a key modification of the vessel. The tank's size and layout impact endurance, deadweight, and cargo capacity. The tank arrangement also affects vessel strength, trim, and stability. To determine the optimal methanol tank size and location, we evaluated various layout alternatives (Figure 6).

Cases A, B, and C consider on-deck tank arrangements. The IMO guideline[12] does not require cofferdams for a methanol tank arranged on an open deck. However, if cofferdams are provided, it is not required to use A-60 insulation for accommodation walls and escape routes or to install a water spray system for the methanol tank walls. To minimize retrofit work, we considered a methanol tank with cofferdams in each case.

Cases D and F consider tank arrangements inside cargo holds. In Case D, the methanol tanks are arranged on both sides of cargo hold No. 6; while in Case F, the tanks are arranged at the bottom of cargo hold No. 6. Distributing the added weight around cargo hold No. 6 gives a better result considering the longitudinal strength.

Case E evaluates replacement of ballast water tanks in the double bottom with methanol tanks. The tank wall facing the outer hull is underwater, and the IMO guideline[12] does not require a cofferdam for the outer hull. Converting a tank from ballast to methanol storage requires changing the paint inside the tank, including special surface preparation before painting. The ballast tanks are narrow with complex steel construction, and painting defects from long-term use must be considered.

Table 4 summarizes key design considerations and shows pros and cons for each tank arrangement.

Figure 6: Tank arrangement options considered for feasibility.

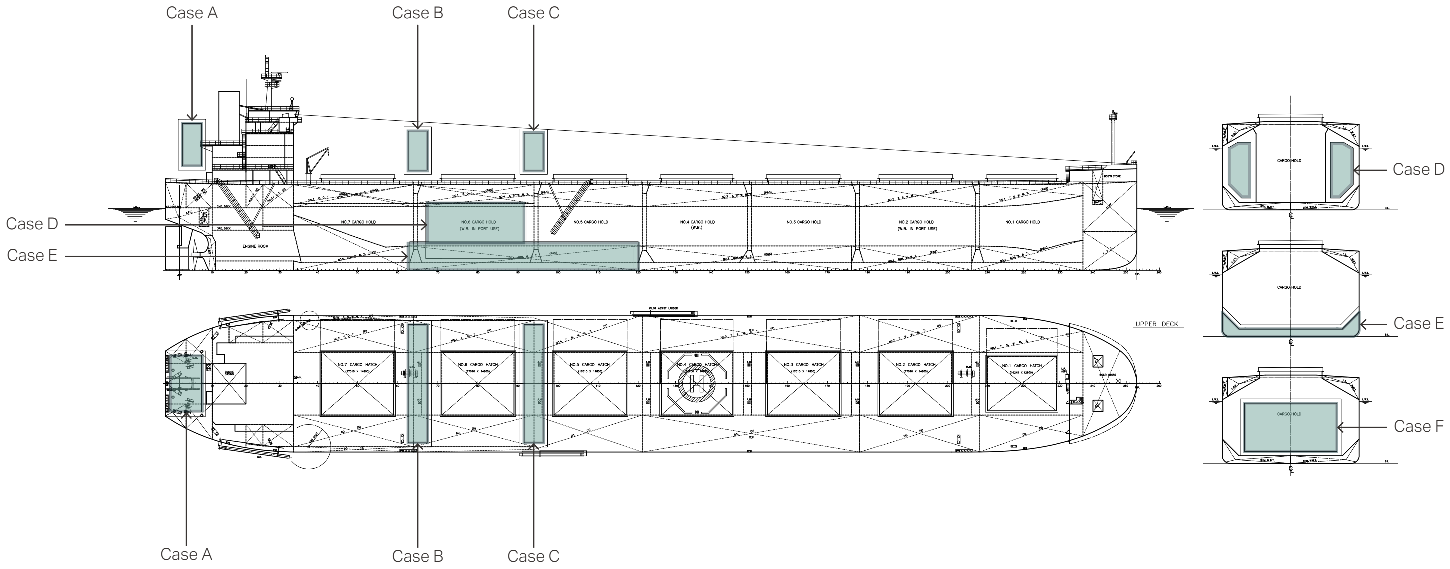


Table 4: Comparison of tank arrangement options.

Case	Tank location	Design considerations	Pros	Cons
Case A	On deck (Accommodation aft)	The concept is to place the methanol tank on deck. The position should be on the upper side of the upper deck, and the influence of adding weight at a higher position should be studied. Normally, there is not enough space on deck, and the methanol tank size should be smaller than the other options considered in Cases D–F.	Easy installation	- Limited tank capacity - High center of gravity - Interference with cargo operation
Case B	On deck (No. 6-7 hold)		Easy installation	
Case C	On deck (No. 5-6 hold)		Easy installation	
Case D	In No. 6 hold (both sides)	Cargo volume should be reduced, but large methanol tanks can be arranged at a lower position than on the upper deck.	Large tank capacity	- Decreased cargo hold volume
Case E	In double bottom	Existing ballast tanks are converted into methanol tanks. Large methanol tanks can be arranged in a lower position. The influence of decreasing the ballast water capacity should be studied. Paint in the tank should be suitable for methanol and the work required to change the paint should also be considered.	- Large tank capacity - Less impact on vessel arrangement	- Effect of conversion from ballast water tanks should be studied - Difficulty welding/ painting in narrow space
Case F	In No. 6 hold (center)	Similar to Case D. The conversion work is easier than in Case D, but the cargo hold with the methanol tank installed cannot be used as cargo hold space.	- Large tank capacity - Easy installation	- One cargo hold is not available, resulting in a significant decrease in cargo volume

We examined Cases A–F and each arrangement's impact (Table 5) on:

- Deadweight
- Volume loss in cargo hold
- Vessel voyage endurance
- Trim and stability compliance
- Longitudinal strength limitations

Table 5: Results of impact assessment for tank arrangements in Cases A–F.

Case	Tank location	Hold capacity (m^3)	Cargo loss — change in DWT (%)	Cargo loss — volume (%)	Methanol capacity (m^3)	Impact on trim	Impact on longitudinal strength (intact /flooded)
Baseline	—	98,000	—	—	—	—	—
Case A	On deck (Accom. aft)	98,000	0.5	0	1,000	Not acceptable*1	Not acceptable*2
Case B	On deck (No. 6-7 hold)	98,000	0.5	0	1,000	Acceptable	Not acceptable*2
Case C	On deck (No. 5-6 hold)	98,000	0.5	0	1,000	Acceptable	Acceptable*3
Case D	In No. 6 hold (both sides)	92,000	1	6	2,500	Acceptable	Acceptable*4
Case E	In double bottom	95,500	0.5	2	3,000	Not acceptable*1	Not acceptable*2
Case F	In No. 6 hold (center)	82,000	1	16	3,000	Acceptable	Not acceptable*2

As Table 5 shows, Cases A, B, E, and F were not feasible because the vessel could not satisfy the trim criteria or could not meet the original allowable longitudinal strength. This means that reinforcements will be required on both local and global levels across the vessel, i.e., impacting the main hull part. Such work affects the time required to retrofit and adds capital expenditure (CapEx) costs.

Cases C and D also did not meet the original allowable longitudinal strength. Therefore, we studied some operational limitations that enable the design to satisfy longitudinal strength requirements.

In Case C, the alternate cargo loading condition has the most severe impact on the longitudinal strength. As Figure 7 shows, alternate loading implies that holds No. 1, 3, 5, and 7 are loaded and holds No. 2, 4, and 6 are empty.

According to our calculation, Case C becomes feasible when alternate loading is not applied. In this case, the vessel can only operate with homogeneous loading, and the class notation “BC-A” should be changed to “BC-B”. The latter cannot use alternate loading and is not a desired operational condition.

In Case D, the additional load of the methanol tank is distributed more homogeneously in the longitudinal direction compared to Case C. This provides better weight distribution and avoids the need for structural reinforcements. However, even though the weight is distributed as evenly as possible in Case D, both the port- and starboard-side No.1 fuel oil tank (see Figure 8) must still be empty when filling the methanol tanks and while the vessel operates with alternate cargo loading. This reduces weight concentration effects and gives the vessel a more balanced longitudinal strength.

DWT = deadweight tonnage

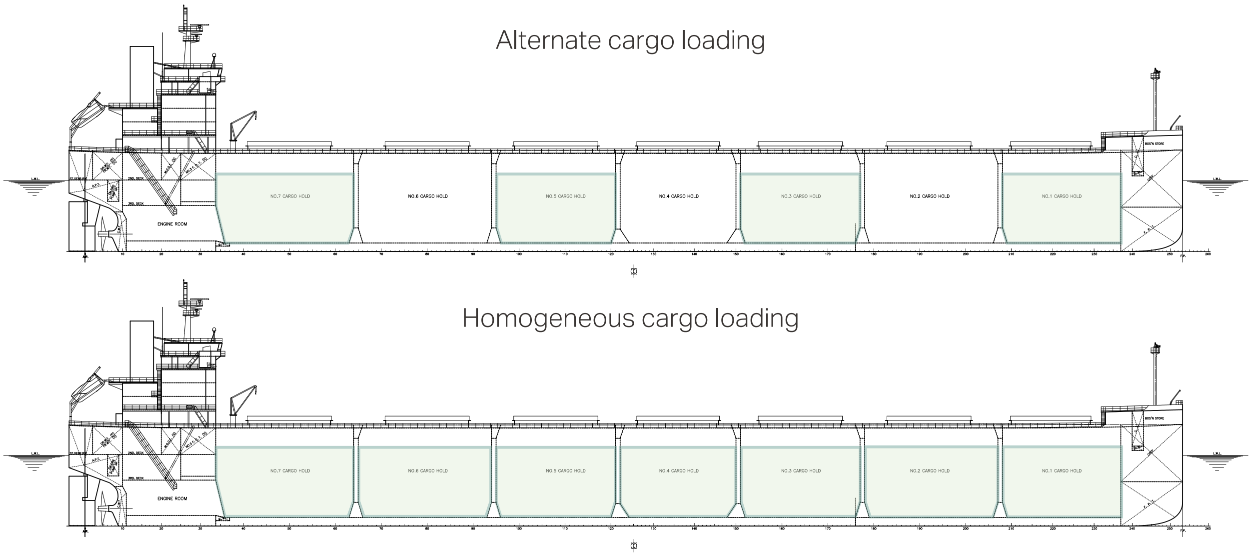
*1 “Not acceptable” indicates that the vessel is unable to make the necessary trim condition due to the additional weight from the conversion.

*2 “Not acceptable” indicates that additional structural reinforcement is required to comply with classification society requirements.

*3 “Acceptable” indicates that the vessel meets the longitudinal strength requirements of the classification society with its existing hull structure, subject to cargo loading limitations.

*4 “Acceptable” indicates that the vessel meets the longitudinal strength requirements of the classification society with its existing hull structure, although two of the six fuel oil tanks are subject to filling limitations.

Figure 7: Cargo loading conditions for (upper) alternate and (lower) homogeneous loading.

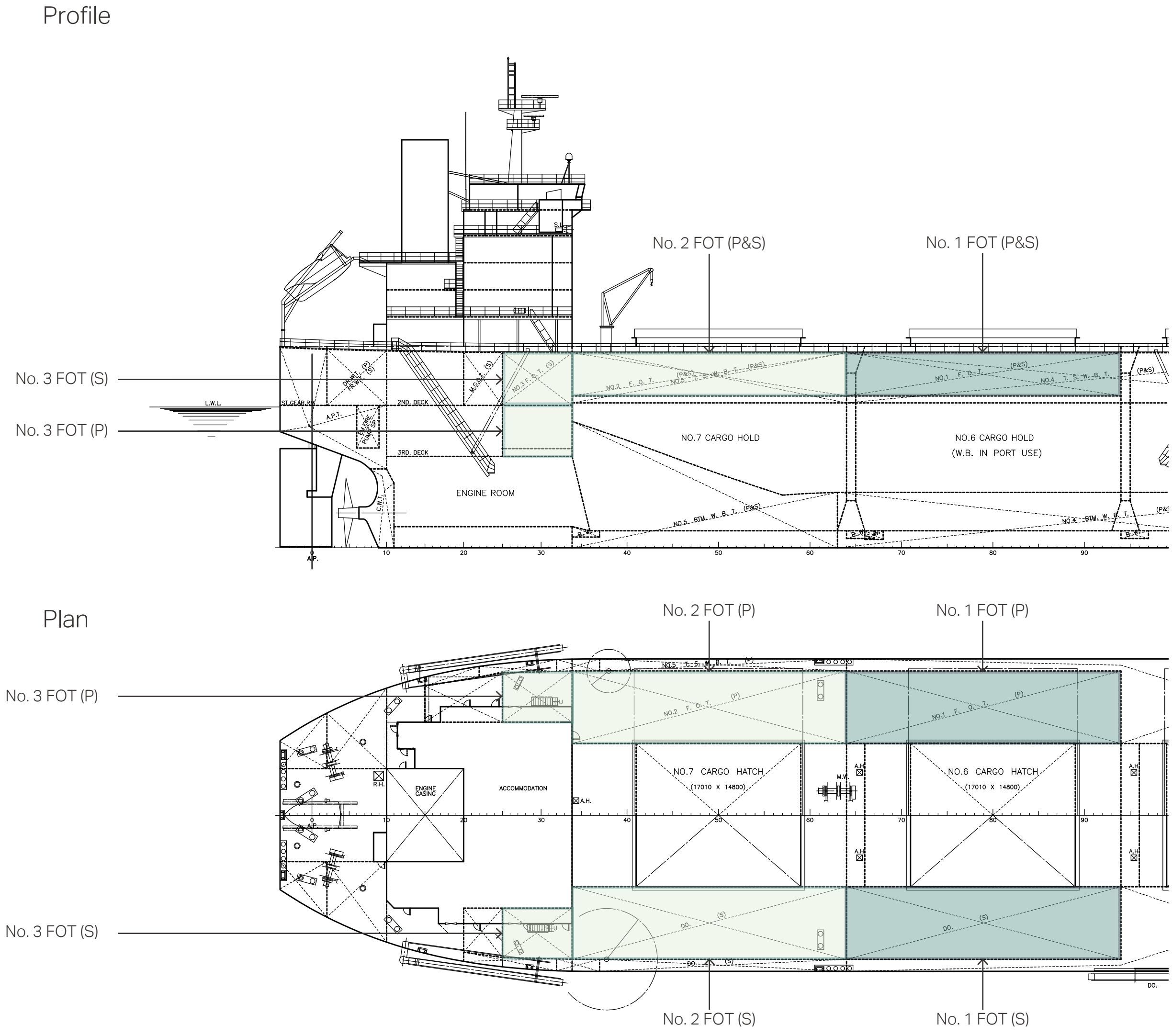


The standard vessel design has six fuel oil tanks with a total capacity of 2,500 m^3. After the retrofit, the vessel's fuel oil consumption will be limited to pilot fuel for the main engine and auxiliary power generation. When both port- and starboard-side No.1 fuel oil tanks must be empty, the available fuel oil tank capacity is 1,460 m^3. Considering the design's methanol tank capacity (2,500 m^3), this reduced fuel oil capacity is sufficient to operate the vessel. As such, this restriction causes no operational limitations.

Based on the above case studies, we identified Case C with cargo loading limitations and Case D with fuel oil tank filling limitations as possible retrofit options. For this study, we selected Case D for further development because:

- The Case C arrangement may negatively influence shore cargo operation due to the high compartment in the cargo handling area
- The Case D arrangement has enough methanol tank capacity for medium-range voyages
- Our studies of combination cases (e.g., small tank capacity of Case A and Case C) did not obtain a better result than Cases C and D

Figure 8: Arrangement of fuel oil tanks in the design selected for further development.



FOT = fuel oil tank, P = port side, S = starboard side

4.2 Detailed design for the chosen retrofit option

4.2.1 Fuel storage

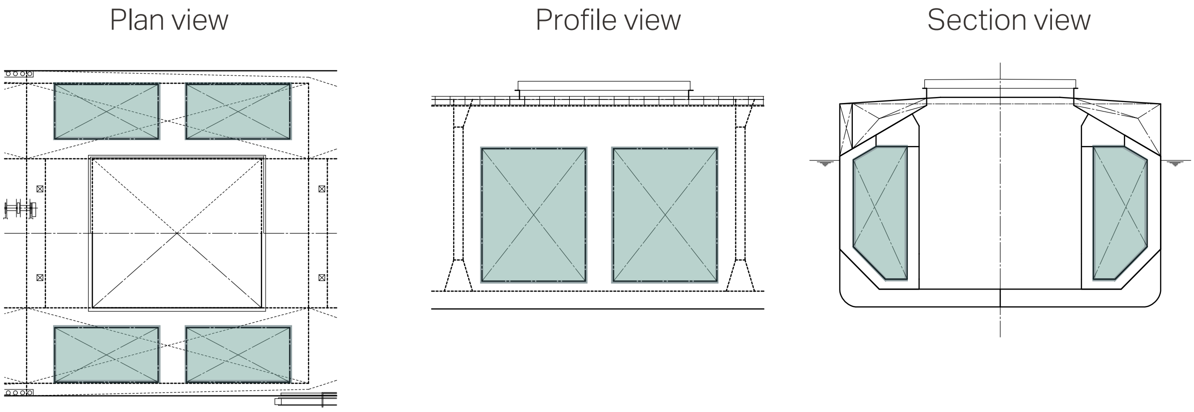
As previously described, we decided to arrange the methanol fuel tanks in the cargo hold. Arranging a large methanol tank in the cargo hold requires removal of topside tanks. If the methanol tank is smaller than the cargo hold opening, the methanol tank can be prefabricated prior to dry docking and installed through the cargo hold opening as an independent tank without cutting a large hole in the hull.

To apply this concept, Figure 9 shows how the methanol tanks in Case D are divided into two tanks/sides. Table 6 presents the main differences between specifications for methanol-fueled and conventionally fueled vessels. The selected arrangement has in-hold tanks on both sides of hold No. 6 and provides a methanol capacity of 2,500 m³.

Table 6: Main differences between conventionally fueled and methanol-fueled vessels.

	Conventionally fueled vessel	Methanol dual-fuel/ converted vessel	Note
Methanol tank capacity	—	2,500 m^3 in total	Capacity of conventional fuel tanks is the same as before the conversion
Hold capacity	98,000 m^3	92,000 m^3	Approx. 6% loss
Deadweight	82,300 tonnes	81,600 tonnes	Approx. 1% loss

Figure 9: Methanol tank arrangement.



4.2.2 Fuel supply system

Besides the methanol storage tank, converting a vessel to methanol dual-fuel operation requires the arrangement of other equipment on board, such as the methanol service tank, low-flashpoint fuel supply system (LFSS), and methanol drain tank. For newbuilds, fuel equipment rooms are provided in suitable positions below the upper deck or next to other compartments. However, such arrangements have disadvantages for retrofit projects:

- Arranging additional fuel equipment on the lower side of the upper deck requires large-scale steel cutting on the upper deck, or side shell, to install the equipment from the outside.

- If the additional compartment is arranged next equipment required for methanol dual-fuel conversion. Therefore, when prepared onshore as modular compartments before dry docking, compartments containing several pieces of equipment can be installed at the same time without extensive welding work on board.

The FPR is located on the aft side of the vessel on the following three decks:

- Upper level: service tank
- Middle level: LFSS and FVT
- Lower level: drain tank

The decks have openings and ladders to enable access to other decks. The FPR is therefore not isolated, which reduces the amount of e.g., ventilation equipment. Figures 10 and 11 show the arrangement of the modularized FPR.

Figure 10: Arrangement of fuel preparation room.

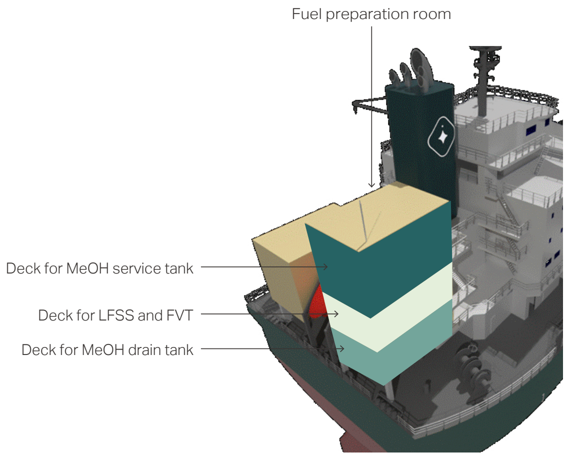
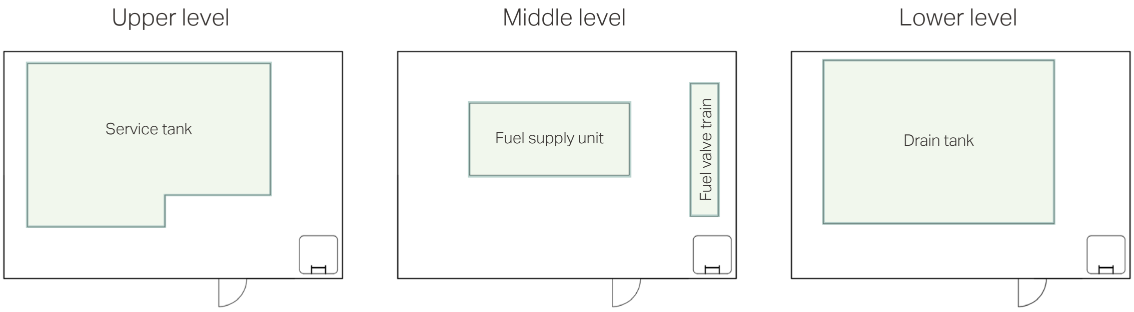


Figure 11: Plan of the fuel preparation room.



MeOH = methanol, LFSS = low-flashpoint fuel supply system

Initially, methanol fuel from the storage tank is transferred to the service tank. Subsequently, the fuel is supplied from the service tank to the LFSS, which regulates the methanol temperature, capacity, and pressure. As Figure 5 shows, the fuel is then supplied to the main engine through the FVT.

Given this fuel transfer process, the service tank should be positioned on the top deck, with the LFSS arranged below this deck, for optimal service tank functioning. The drain tank should be placed at the lowest possible level to collect drains from various locations. The pressure loss in the fuel piping (LFSS to FVT and FVT to main engine) has been accounted for in the required fuel supply pressure at the engine, according to limits specified by Everllence.

For emergency situations, each deck has two escape routes: a vertical ladder leading to another deck and a door providing access to the open deck.

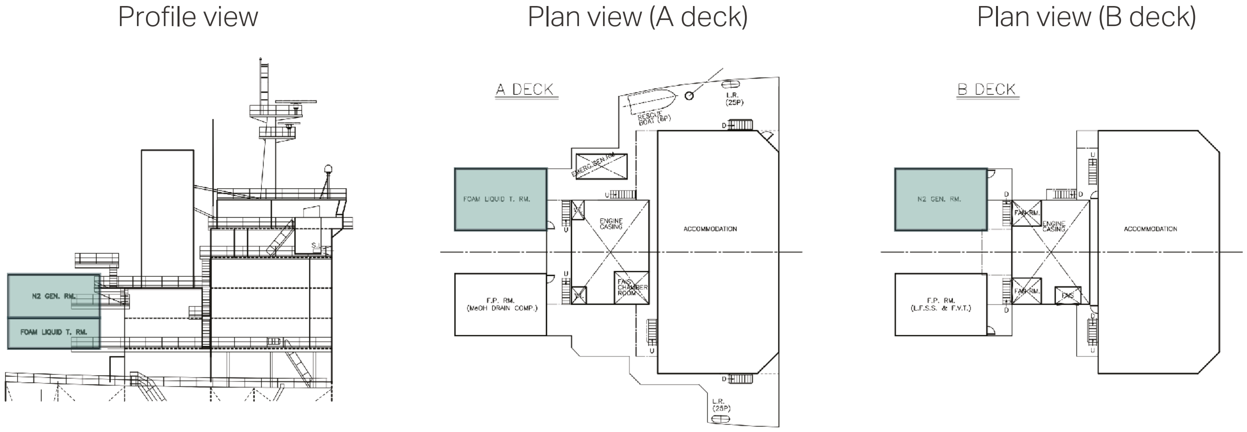
4.2.3 Nitrogen system and alcohol-resistant foam firefighting system

Safe handling of methanol requires nitrogen for, e.g., inerting of methanol tanks and for purging of pipes. Therefore, nitrogen generators and piping should be added when converting to methanol operation.

To reduce the retrofit work, the design uses a modular compartment as the nitrogen generator room. The location is on the aft side of the accommodation. Figure 12 shows the arrangement of the nitrogen generator unit, compressors, and nitrogen reservoirs.

An alcohol-resistant foam firefighting system is required in areas where a methanol leak may occur. Normally, the foam is mixed with seawater and delivered to the protected area through foam monitors or sprinklers. For conversion to methanol, such a system should be added. The main components are a foam tank and a pump. A dedicated room is provided for the firefighting system and combined with the module for the nitrogen generator (Figure 12).

Figure 12: Arrangement of nitrogen generator room and foam liquid tank room.


Profile view

Plan view (A deck)

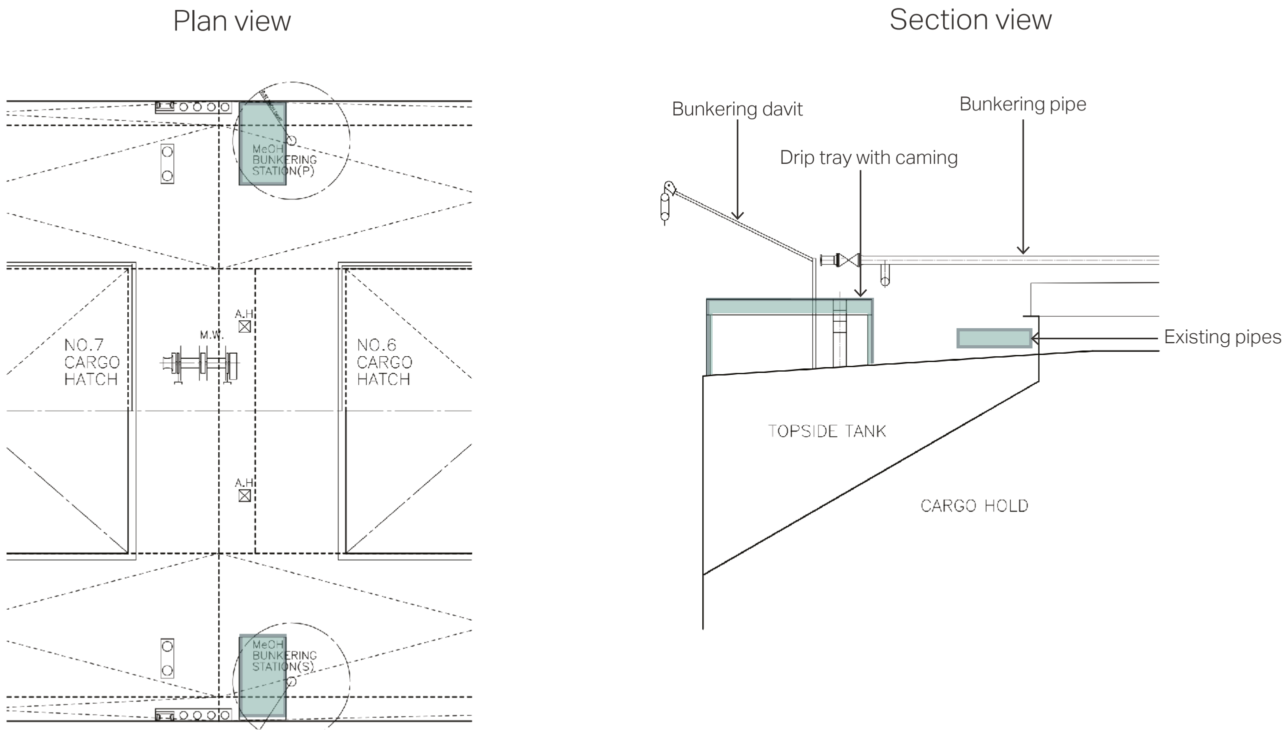
Plan view (B deck)

4.2.4 Bunker station design

Dedicated methanol bunker stations are essential for the supply of methanol fuel on board. To minimize the length of the bunker line, these stations should preferably be located near the methanol storage tank.

Considering safety and equipment impacts, the bunker stations are placed on the cross deck between cargo holds No. 6 and No. 7, as shown in Figure 13. To minimize modification work on the existing outfitting, the bunker stations are positioned approximately two meters above the upper deck.

Figure 13: Arrangement of bunker stations.



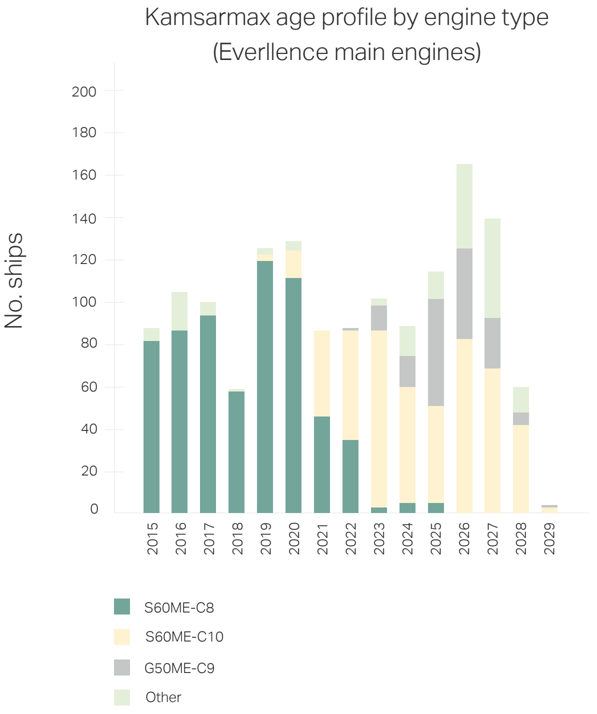
Plan view

Section view

4.3 Main engine

Several types of conventionally fueled main engines have been delivered for 82,000 DWT bulk carriers. For this feasibility study, we selected the Everllence B&W 6S60ME-C10.5-EGRBP (exhaust gas recirculation bypass) engine, which is suitable for retrofitting to methanol dual-fuel operation. As Figure 14 shows, the S60ME-C10 engine was introduced in 2019. Considering the vessel age and market share for Kamsarmax bulk carriers, this engine model is suitable for this study.

Figure 14: Application of Everllence main engine model (S60ME-C10.5) for Kamsarmax bulk carriers. Data source: Clarksons Research.



4.4 Engine retrofit kit

A retrofit kit can be used to convert the engine to methanol operation.[13] The kit adds the following systems and functionalities (Figure 15):

1. Fuel booster injection valves for injection of methanol (FBIVM) into the combustion chamber

2. Hydraulic control oil system for controlling FBIVM operation

3. Sealing oil supply unit, which supplies sealing oil to moving parts of the methanol injection system to ensure that control oil is not contaminated with methanol; the unit is mounted on the engine

4. Double-walled fuel piping to distribute methanol to individual cylinders, ensuring confinement of any methanol leak within the space between the inner and outer piping

5. Draining and purging system for quick and reliable removal of methanol from the engine

6. An additional safety system to monitor the methanol injection and combustion and to ensure that the engine reverts to diesel oil operation if necessary

7. An FVT that provides a block-and-bleed function between the LFSS and the engine

The retrofit conversion will enable the engine to run in two modes, i.e., on fuel oil in fuel oil mode and on methanol in dual-fuel mode.

Figure 15: Single cylinder of liquid gas injection methanol (LGIM) engine[13 ver. 1] and main LGIM system components.[13]

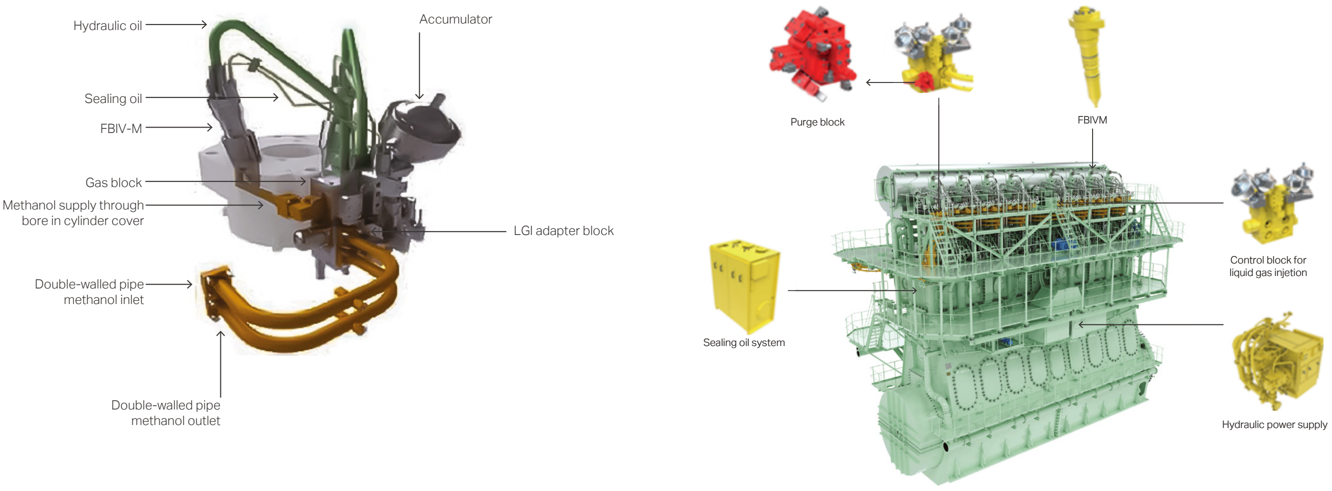
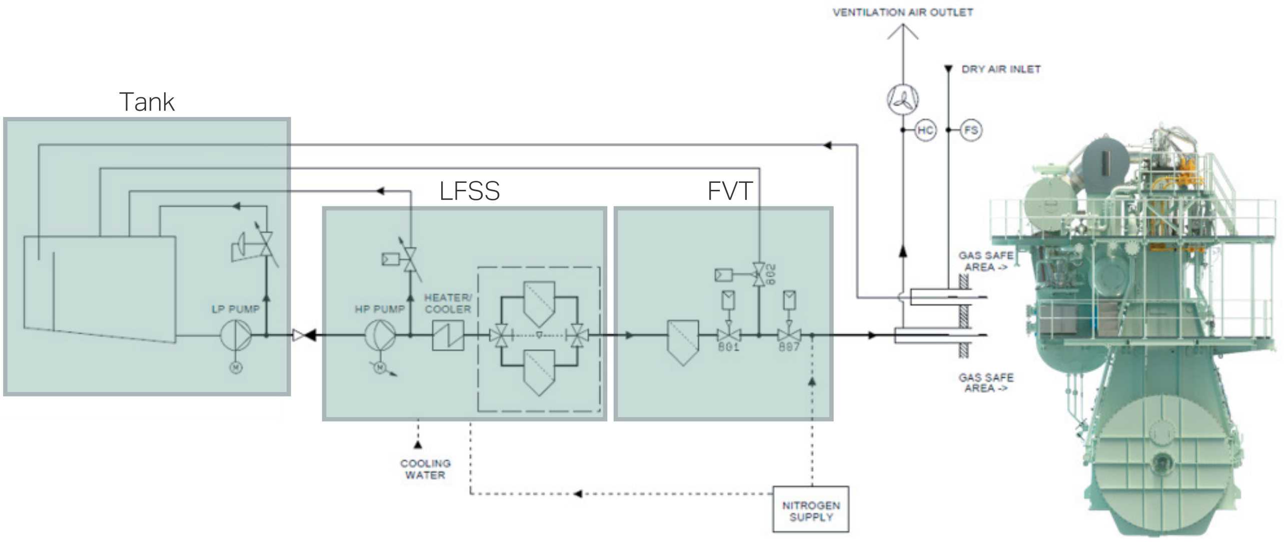


Figure 16: Overview of auxiliary systems for the main engine.[13]



Principle flow diagram for ME-LGIM auxiliary system. Not to be used as design basis.

When running in dual-fuel mode, a small pilot injection of conventional fuel initiates the combustion of methanol. Very low-sulfur fuel oil (VLSFO), marine gas oil (MGO), sustainable biofuel, or synthetic fuel can be used as pilot oil. The expected pilot oil fraction for dual-fuel operation is 5%.[13]

The Everllence retrofit scope covers the conversion of the main engine, including the FVT. In addition, a full conversion project consists of the installation and integration of the methanol bunker and storage system, methanol service tank, LFSS, and a nitrogen system for purging purposes, which are delivered by the shipyard of choice. Figure 16 shows an overview of fuel-related auxiliary systems for the main engine.

FBIVM = fuel booster injection valve for methanol
LFSS = low-flashpoint fuel supply system, FVT = fuel valve train, LP = low pressure, HP = high pressure, HC = hydrocarbon, FS = flow switch

Before preparing the engineering work/drawings for the methanol engine conversion kit, a team from the engine manufacturer (Everllence) will carry out an engine pre-inspection and 3D scanning. This includes measurements, photo documentation, and other relevant information about the vessel to be converted. Other components that need overhaul due to wear and tear (e.g., cylinder liners, stuffing boxes) are not part of the retrofit kit.

During the engine conversion, superintendent engineers from the engine manufacturer will consult and guide the shipyard workers. Estimated time needed for the shipyard to support the engine manufacturer is approximately 9,000 hours.

After the engine conversion, commissioning can follow the steps below:

1. Quay trial
2. Sea trial (on fuel oil)
3. Second fuel trial (dual-fuel operation on methanol)

4.4.1 Pilot fuel arrangement

For methanol conversions, a completely new cylinder cover is provided with extra holes for the methanol equipment.

Two types of injectors (valves) are mounted on the new cylinder cover: FBIVM and fuel injection valves (FIV). The FBIVM has been designed as a batch-injector, combining a hydraulically actuated plunger pump with a spring-held injection needle valve that opens at a given fuel pressure. The pump functionality of the FBIVM uses hydraulic pressure to increase the methanol pressure from the LFSS supply pressure (13±0.5 bar) to the required injection pressure of approximately 600 bar. A suction valve (check valve) ensures filling of the pump chamber after each stroke.

The FIV provides a small pilot oil injection from the diesel fuel system to ignite the methanol. To optimize the ignition of the methanol fuel jets, the FIV is positioned clockwise relative to the FBIVM.

4.4.2 Electricity consumption study

As Table 7 shows, the additional equipment required for operation on methanol fuel increases the vessel's electricity consumption. Based on our calculations, a power increase of approximately 100 kW can be expected after retrofitting the vessel to run the LFSS, nitrogen generator system, mechanical ventilators for extra compartments, and other related components. However, the standard vessel design proposed has sufficient generator capacity to accommodate this increase. Therefore, no design changes were made to the generators.

Table 7: Generator capacity and electricity demand before and after the conversion.

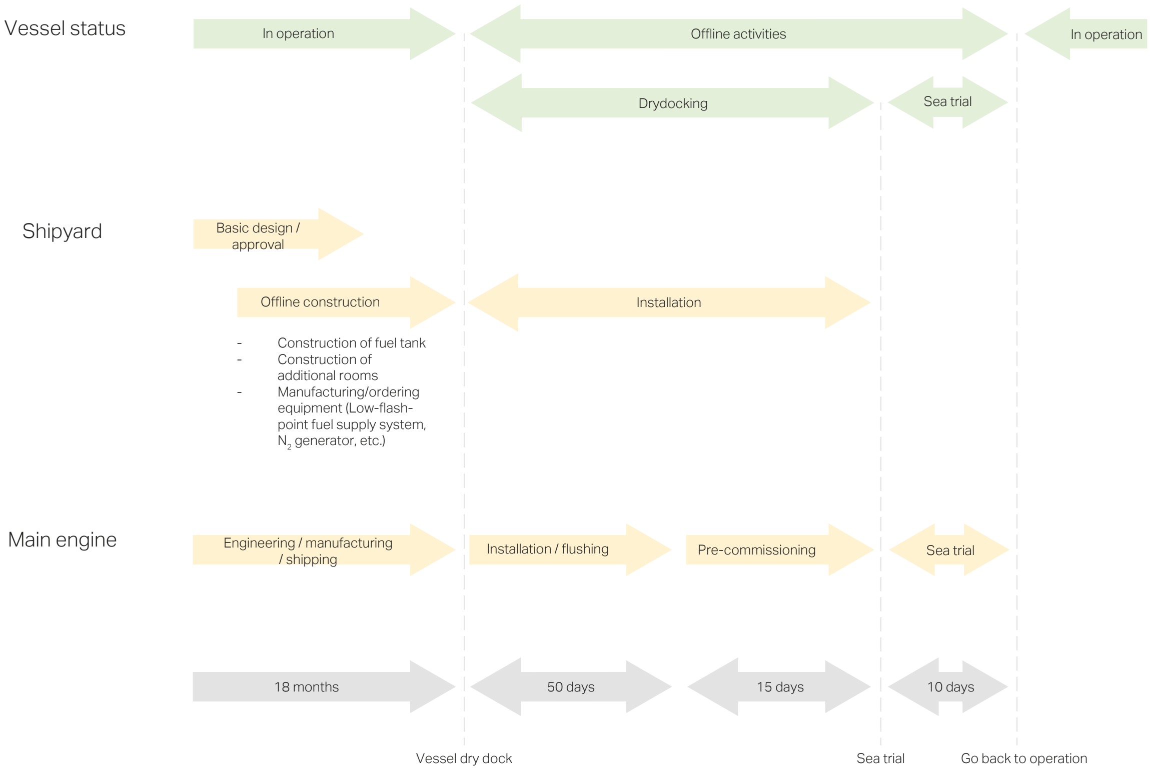
	Before conversion	After conversion
Electricity demand for normal operation	370 kW	470 kW
Generator capacity	610 kW	610 kW
Load rate	60%	77%

4.5 Lead time estimation for retrofit work

Due to off-hire costs, the time spent in dry dock while retrofitting the assets is one of the most important factors to consider in this study. For this project, the solution has been carefully considered to enable much of the work to be done prior to docking the vessel or offline.

Figure 17 shows offline activities for both the shipyard and the original equipment manufacturer for the main engine. The activity positioned immediately adjacent to the critical path of the retrofit execution during dry dock is the main engine conversion.

Figure 17: General shipyard schedule aligned with main engine conversion schedule.



For this project, the timeline for conversion work was estimated to be 60 days plus a sea trial period of 15 days. The former period includes the installation of the storage tank and fuel preparation rooms. The estimated timeline for work prior to dry docking was approximately 1.5 years. This is the time required to produce the offline parts, as well as to complete the pre-work needed for engineering, manufacturing, and shipping of the main engine retrofit parts.

05 Shipyard integration considerations

The methanol tank is made of steel and must be painted with inorganic zinc paint, requiring specific surface preparation. Prefabricated methanol storage tanks minimize the work needed for applying inorganic zinc paint after installation.

For our design, the estimated weight of one methanol storage tank is approximately 130 tonnes. If the shipyard lacks cranes to handle such heavy components, the prefabricated tank should be divided into multiple parts to reduce the weight.

The retrofit lead time can be kept short by introducing the methanol storage tank through the opening of the cargo hold. Accordingly, the size of our tank design is determined by the dimensions of the cargo opening, including an allowance of approximately 1 meter on each side between the edge of the opening and the tank wall.

After the installation, horizontal and vertical steel plates must be welded to the external side of the tank to integrate it into the cargo hold. The welding work could damage the inorganic zinc paint. Therefore, the welding area on the methanol tank should be planned with consideration for this potential damage.

Installing and integrating the methanol tank may require specialized techniques and tools, such as leveling techniques when welding the divided tanks.

High: Unacceptable	Additional safeguards should be taken to reduce the risk to medium or low
Medium: As low as reasonably practicable (ALARP)	Additional safeguards should be taken as far as reasonably practicable
Low: Widely acceptable	No additional risk reduction measure is required

06 Risk assessment

In accordance with MSC.391(95) (IGF Code) and MSC.1/1621, a risk assessment is required before operating on methanol fuel.

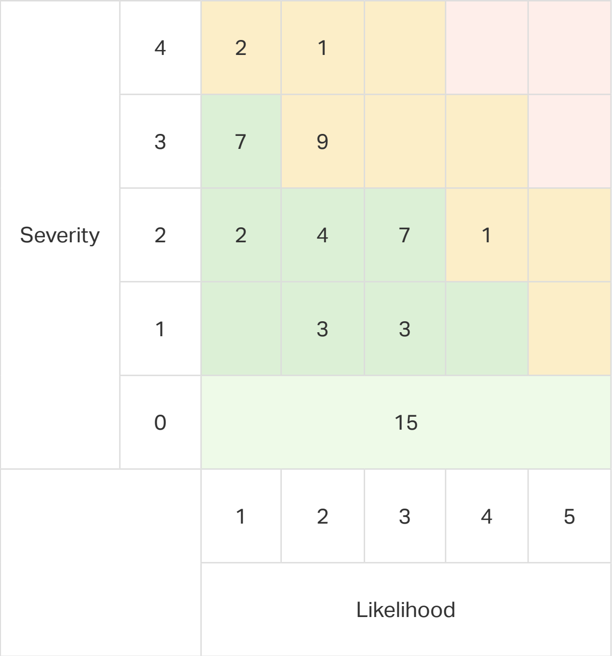
As part of this project, technical and operational experts joined a HAZID workshop to identify potential hazards associated with the conversion to dual-fuel methanol operation. The objective of the HAZID was to identify and analyze the major hazards of the system that may affect the feasibility of the design concept.

Table 8 outlines the severity and likelihood of risks identified during the HAZID. A total of 54 risks were identified. However, we found no high-risk items that required additional mitigative measures beyond the inherent safeguards applied to the existing design.

The risk assessment identified 39 hazards, of which 13 were rated as medium and 26 as low. Table 15 in Appendix A provides an overview of the highest-rated hazards identified.

Additional safety measures to reduce the risk level from medium to low were also discussed during this HAZID workshop, as shown in Table 9.

Table 8: Risk matrix from the HAZID workshop.



Severity	4	2	1			
	3	7	9			
	2	2	4	7	1	
	1		3	3		
	0	15				
		1	2	3	4	5
		Likelihood				

Table 9: Additional safeguards to mitigate the identified main hazards.

System	Additional safeguard
Storage tank	- Add N_2 connection points for the TCS - Establish a contingency plan for methanol leakage in the TCS
FPR	- Provide a method to check methanol vapor concentration in the FPR before entering the room - Establish operational procedures such as using personal protective equipment
Vent mast	Conduct general study of gas dispersion from vent mast
Bunkering	Consider redundancy for related equipment
Fuel supply system	(Same as for the storage tank)
Electrical system	Establish an emergency procedure including sequence flow diagram for blackout incidents
Fire detection and protection system	Establish emergency response procedures
Lifesaving and evacuation system	Consider installing an explosion relief valve on the FPR
Bunkering	—
Daily inspection /maintenance	Install the indicators to confirm the status of the entrance door or hatch for the spaces where methanol may be present

TCS = tank connection space, FPR = fuel preparation room

07 Economic analysis

Here, we present an overall economic assessment of the retrofit solution described in the previous sections.

The economic analysis has been divided into two parts:
- Dedicated CapEx cost-delta analysis of dual-fuel methanol retrofit versus single-fueled vessel
- Financial modeling of discounted cash flows over a 20-year horizon, evaluating the financial viability of a retrofit investment by calculating the present value of future cash flows

The analysis considers the following cost factors:

- Dry docking conversion costs
- Vessel off-hire to finish the retrofit
- Lost revenue due to reduced cargo capacity after conversion
- Fuel costs
- Impacts of the European Union Emissions Trading System (EU ETS) and the IMO Net-Zero Framework (NZF) as agreed at the 83rd session of the Marine Environment Protection Committee (MEPC 83)

Furthermore, we calculated the potential GHG emissions reductions from implementing such a retrofit. We do not include further comparisons with retrofitting to other low-carbon fuels.

7.1 CapEx cost delta analysis: retrofit versus single-fuel vessel

Table 10 shows the cost categories used for the cost analysis and the sources for cost assumptions.

Table 10: Construction cost evaluation of methanol retrofit work.

Cost	Cost based on	
CapEx	Main engine conversion	Insight from project partners
	Tank cost	Market insights from project partners and calculations based on steel materials, steel weight, and painting
	Coating methanol tanks	Insight from project partners
	Equipment (fuel supply systems, etc.)	Insight from project partners
	Yard installation, labor, and design cost	Experience of project partners
	Off-hire cost	TCE and retrofit working days, in addition to insights from project partners
OpEx	Reduced time charter cost due to reduced cargo carrying capacity	Insight from project partners

CapEx = capital expenditure, OpEx = operating expenses, TCE = time charter equivalent

Figure 18 presents the cost delta versus the current price of a newbuild single-fuel Kamsarmax vessel at current market value.

The additional CapEx delta to retrofit an existing vessel for methanol capability is estimated at 25-30%, factoring in some uncertainties related to price fluctuations in steel and other machinery components. The assumed newbuilding price for a fuel-oil Kamsarmax bulk carrier is 38-42 million USD.

Breaking down the additional retrofit cost further, the primary expense is related to the main engine conversion (see Section 3). The second-largest expense is associated with equipment, including the various components necessary for methanol conversion (e.g., additional fuel pipes, methanol detectors, firefighting equipment, methanol transfer pumps, and LFSS). Within this category, the LFSS represents the most significant cost. Labor and design costs vary depending on the selected shipyard, while expenses also fluctuate based on material costs and other factors. Therefore, this result should be viewed as illustrative only.

7.2 Twenty-year financial modeling evaluating a retrofit investment

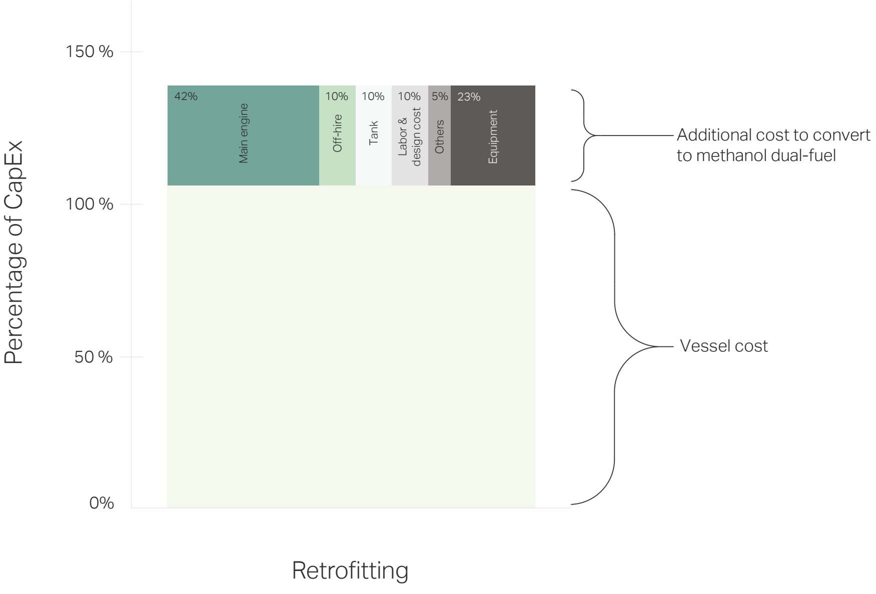
7.2.1 Financial base case and sensitivity analysis rationale

Table 11 offers an overall explanation of the financial base case for our modeling, as well as the rationale for the project's sensitivity analysis.

Table 11: Overview of financial modeling cases.

	Condition	Purpose
Base case	With/without regulation	1. To understand the impact of regulation on the cost gap between Scenario 1 (BAU) and Scenario 2 (retrofit) 2. To compare Scenario 1 (BAU) and Scenario 2 (retrofit), assuming regulations are in place
Sensitivity case	Modeled bio-methanol price required for retrofit to break even in 2050	1. To understand how different bio-methanol prices could impact the retrofit case

Figure 18: Results of the construction cost estimation study.



CapEx = capital expenditure, BAU = business as usual

7.2.2 Main assumptions for the calculations

This section presents a discounted cash flow calculation for the duration of an asset's lifetime. In this modeling, the asset is retrofitted to methanol operation in 2030, five years after beginning operation as a fuel oil vessel (Figure 19). The financial calculations presented in this section use a discount factor of 7% and no additional risk factor.

Trade route assumptions

As Table 1 shows, there are several voyage routes for 82K DWT bulk carriers. For the sake of these financial calculations, we have chosen route P1 (hereafter 'Atlantic route') and route P6 (hereafter 'Pacific route') to represent both short and long-haul trade patterns for such a vessel. The two trade routes are shown in Figure 20.

Figure 19: Timeline and scenarios for the financial calculations.

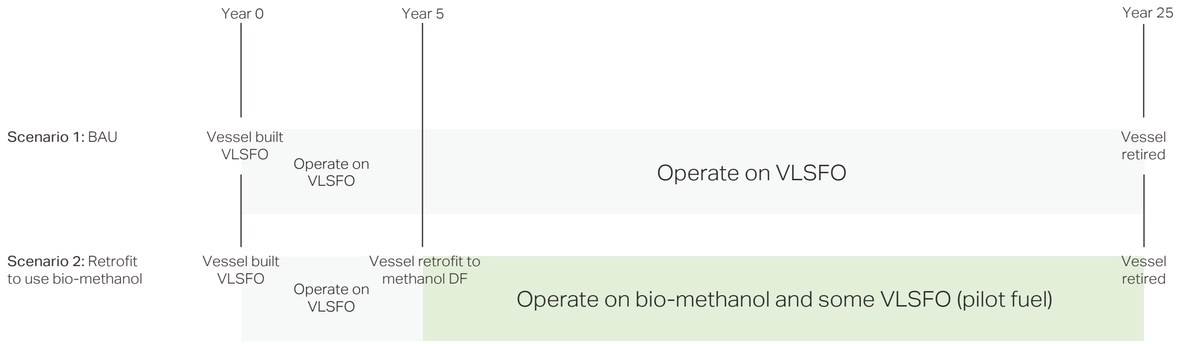
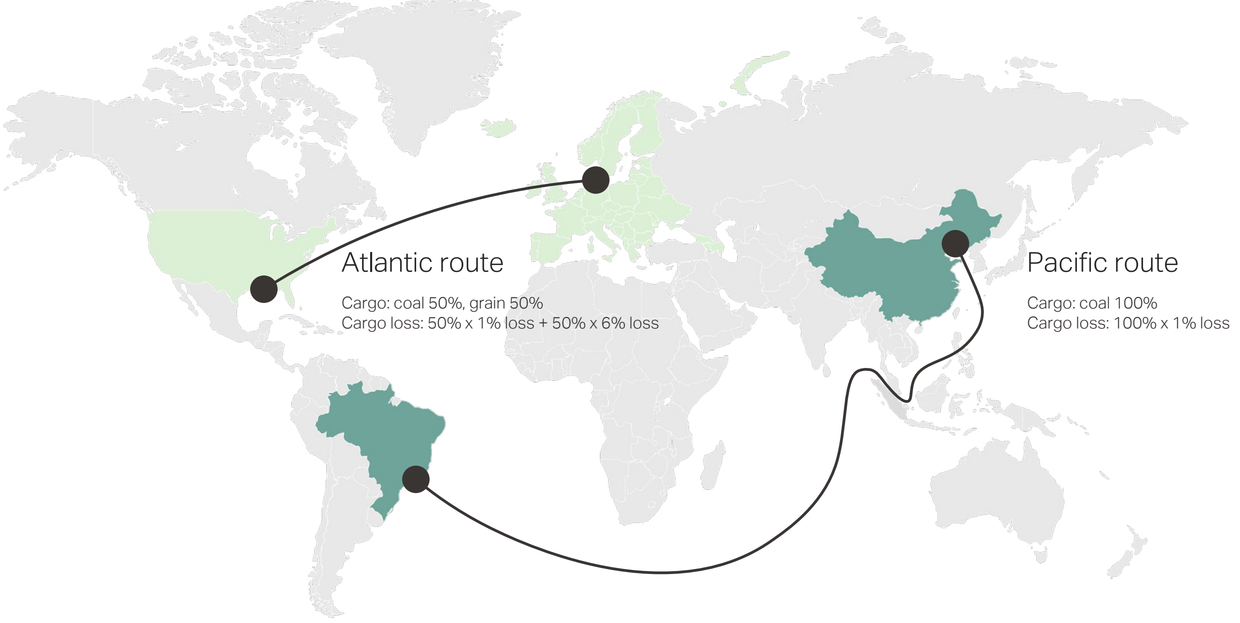


Figure 20: Voyage routes for the Atlantic and Pacific trade routes used in modeling.



BAU = business as usual, DF = dual fuel, VLSFO = very low-sulfur fuel oil

As described in Figure 19, we use two scenarios for our discounted cash flow calculations. In Scenario 1 (BAU), the vessel uses conventional fuel until 2050. In Scenario 2 (retrofit), the vessel converts to dual-fuel methanol operation in 2030 and thereafter uses bio-methanol as the main fuel.

The Atlantic route connects Northern Europe and the Eastern United States. This route includes an emission control area (ECA), where the use of very low-sulfur fuel is required. For this reason, some MGO consumption is considered only for the Atlantic route, and only when the vessel operates inside an ECA. Heavy fuel oil (HFO) is used for the rest of the voyage. The calculation also considers the impact of the EU ETS.

Time charter equivalent assumptions

For this study, we assume that the value of the TCE for conventionally fueled vessels is 16,500 USD/day. For the sake of simplicity, we also assume that this value does not change over time.

The vessel's deadweight and cargo volume will both be lower after conversion to methanol operation. We assume that the cargo for the Atlantic route is coal and grains, and that the cargo for the Pacific route is mainly coal. The lower cargo volume affects the number of grains, and the lower deadweight affects the volume of coal. We reflect these conditions in the assumed TCE for each case.

Fuel and energy source assumptions

This analysis assumes that bio-methanol is the main fuel after vessel conversion. We did not consider gray methanol as a fuel option. The price of bio-methanol, as well as HFO and MGO, is shown in Table 12 and is assumed to remain the same over the 20-year timeline.

Table 12: Assumed fuel prices for HFO, MGO, and methanol. Data source: Argus Media.

	Input (USD/tonne)
HFO	595
MGO	680
Bio-methanol	1,060

We assume that the vessel remains fitted with the same technologies and operational efficiency measures and that it does not undergo any major energy-efficiency upgrades during its remaining lifetime.

For this study, the following options have been left out of scope:
– Use of sustainable bio-oils as a fuel
– Use of other zero- or near-zero-emission technologies, such as wind-assisted propulsion, direct electrification, and onboard carbon capture

Regulatory assumptions

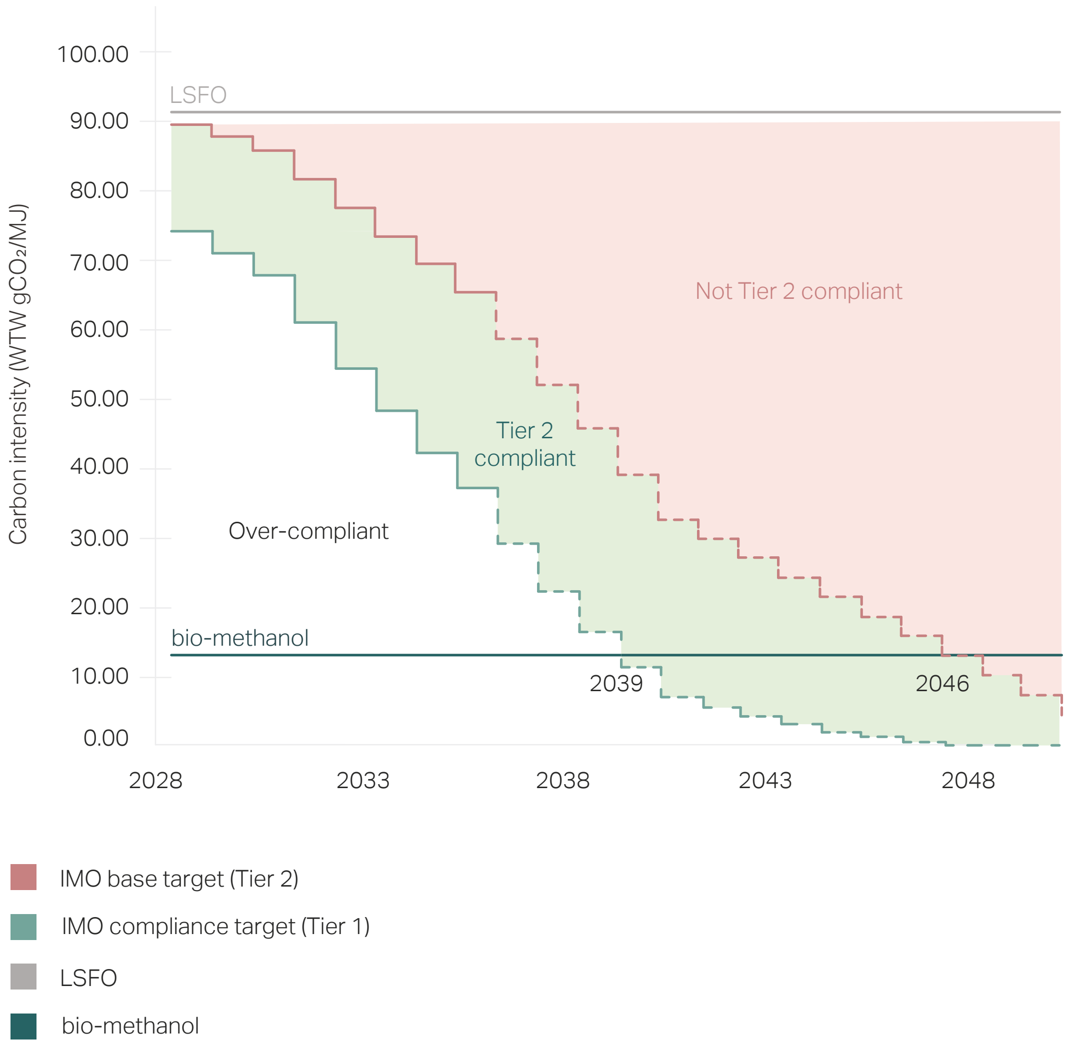
The greenhouse gas fuel intensity (GFI) cost, as described in draft amendments to MARPOL Annex VI approved at MEPC 83,[14] is reflected in our GFI cost calculation. Adoption of this regulation is under discussion at the time of writing. Table 13 and Figure 21 provide our assumptions for the GFI cost calculations based on the approved draft amendments.

Table 13: Inputs for GFI cost calculations.

Item	Input	Note
Annual GFI reduction factor	See Figure 21	Target values after 2035 are not determined yet
RU price	RU1 (Tier 2 compliant): 100 USD/t-WTW CO_2 RU2 (Not Tier 2 compliant): 380 USD/t-WTW CO_2	- RU price after 2031 will be revised - We used the pre-2030 RU price for the entire modeled time horizon
SU price	285 USD/t-WTW CO_2eq	- Based on the assumption that SU price will not exceed the price of bio-diesel - The over-compliant values can be used for the 'Not Tier 2 compliant' range
ZNZ fuel reward	175 (2030)–12.5 (2040) USD/t-WTW CO_2eq[15]	- Bio-methanol may be categorized as a ZNZ fuel - This estimate is based on MMMCZCS assumptions[15] - The reward term is 2030–2040

HFO = heavy fuel oil, MGO = marine gas oil, GFI = greenhouse gas fuel intensity, RU = Remedial Unit, SU = Surplus Unit, WTW = well-to-wake, ZNZ = zero- or near-zero-emissions

Figure 21: Assumed GHG fuel intensity (GFI) reduction factors (Z-factors).



LSFO = low-sulfur fuel oil

Assumptions summary

Table 14 summarizes all the relevant assumptions and inputs to the discounted cash flow calculation.

Table 14: Inputs for discounted cash flow calculation (Atlantic route and Pacific route).

Item		(Scenario 1) Conventionally fueled vessel	(Scenario 2) Vessel with methanol-fueled conversion	Note
Principal particulars of vessel		Refer to Table 2	Refer to Appendix B	
Delivery year of conventionally fueled vessel		2025		
Conversion year for methanol-fueled vessel		—	2030	
Recycled year of vessel		2050		
Discount rate based on 2030		7%		
Fuel price	HFO	14.5 USD/GJ (595 USD/t)		Initial price:Based on information from Argus Media
	MGO	15.9 USD/GJ (680 USD/t)		
	Bio-methanol	53.0 USD/GJ (1,060 USD/t)		
Vessel speed	Laden	11.5 knots		
	Ballast	12.5 knots		
WTW GHG intensity for IMO GFI cost[16, 17]	HFO	95.48 t-WTW gCO$_2$eq/MJ		
	MGO	93.93 t-WTW gCO$_2$eq/MJ		
	Bio-methanol	12.86 t-WTW gCO$_2$eq/MJ		Based on EU RED
TTW GHG intensity for EU ETS	HFO	78.24 gCO$_2$eq/MJ		Based on FuelEU Maritime
	MGO	76.37 gCO$_2$eq/MJ		Based on FuelEU Maritime
	Bio-methanol	0 g CO$_2$eq/MJ		EU ETS allows to account for CO$_2$ emissions of biofuel as zero which complies with the criteria
EU ETS trade cost		155–325 USD/t-TTW CO$_2$eq [18]		- 50% of this cost is reflected in Atlantic route voyage - No cost for Pacific route voyage
For Atlantic trade study				
Fuel consumption	HFO	3,390 t/year	770 t/year	
	MGO	1,350 t/year	690 t/year	For ECA voyage
	Bio-methanol	—	6,970 t/year	
TCE		16,500 USD/day	15,922 USD/day	Considering the cargo loss due to conversion
For Pacific trade study				
Fuel consumption	HFO	4,780 t/year	1,490 t/year	
	MGO	—	—	
	Bio-methanol	—	6,900 t/year	
TCE	16,500 USD/day	16,335 USD/day		Considering the cargo loss due to conversion

ECA = emission control area, EU ETS = EU Emissions Trading System, EU RED = EU Renewable Energy Directive, GFI = greenhouse gas fuel intensity, HFO = heavy fuel oil, MGO = marine gas oil, TCE = time charter equivalent, TTW = tank-to-wake, WTW = well-to-wake

7.2.3 Results of financial calculations

This section shares the results from our financial calculations, both the retrofit scenarios and the sensitivity analysis for bio-methanol pricing.

First, for Scenario 1 (BAU), we wanted to understand the impact of current (EU ETS) and future (IMO Net-Zero Framework, NZF) regulations regulations for the two routes (Figures 22 to 25).

Figure 22: Modeled impact of EU ETS and IMO NZF regulations in Scenario 1 (BAU) for the Atlantic route.

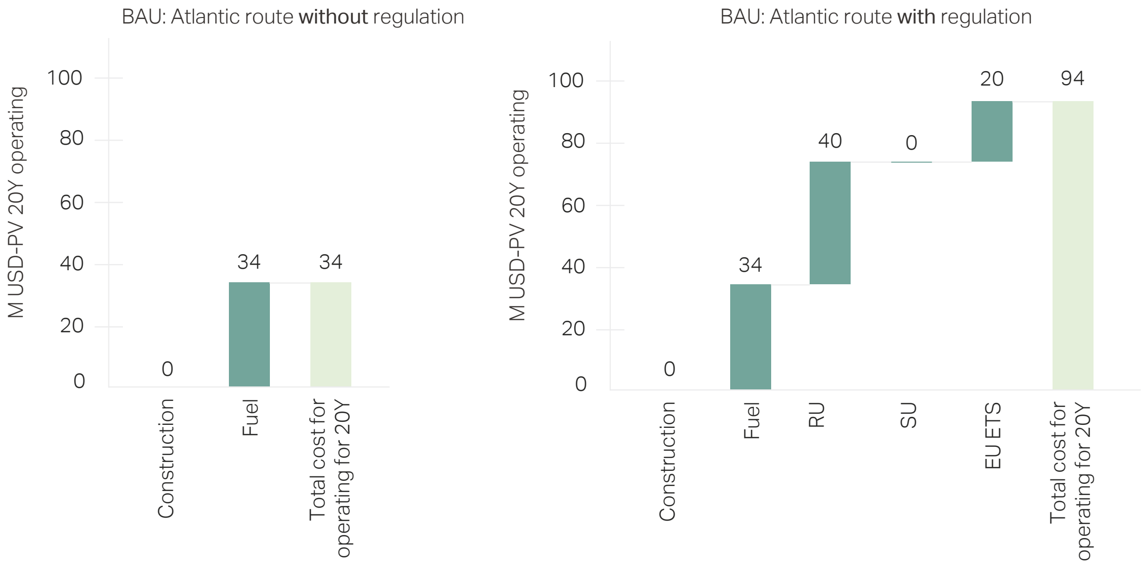
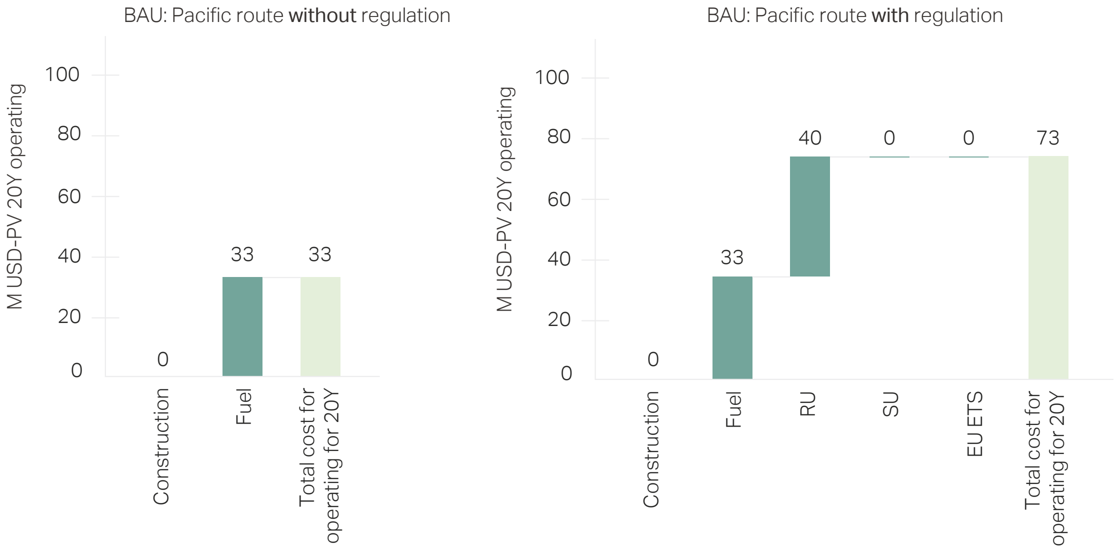


Figure 23: Modeled impact of EU ETS and IMO NZF regulations in Scenario 1 (BAU) for the Pacific route.



BAU = business as usual, PV = present value, RU = Remedial Unit, SU = Surplus Unit, EU ETS = EU Emissions Trading System, IMO NZF = IMO Net-Zero Framework

Figure 24: Cost gap for Scenario 1 (BAU) versus Scenario 2 (methanol retrofit) for the Atlantic route (with regulation).

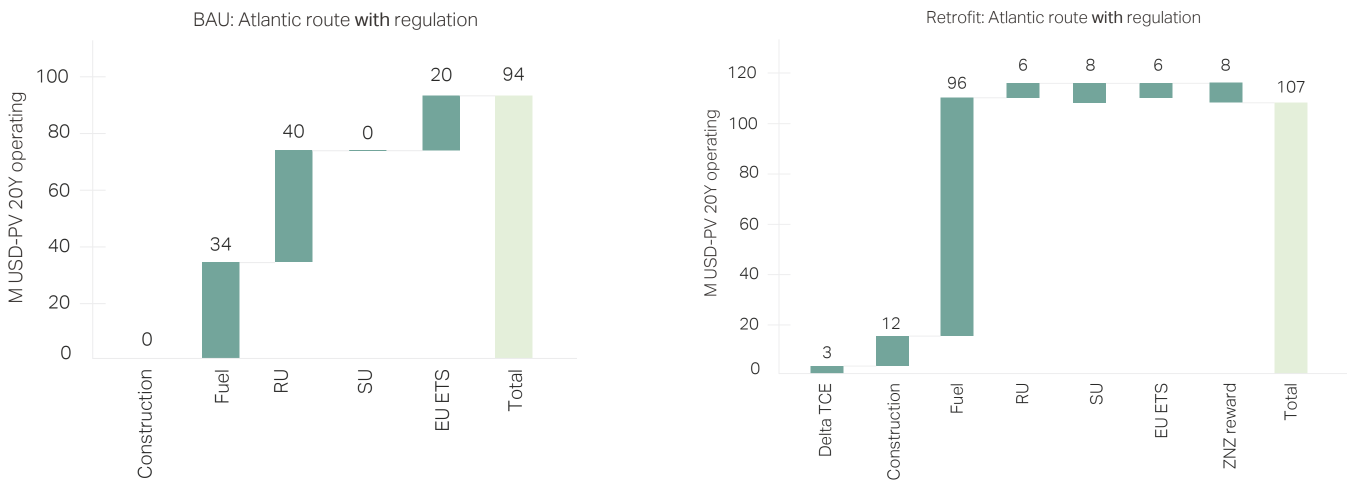
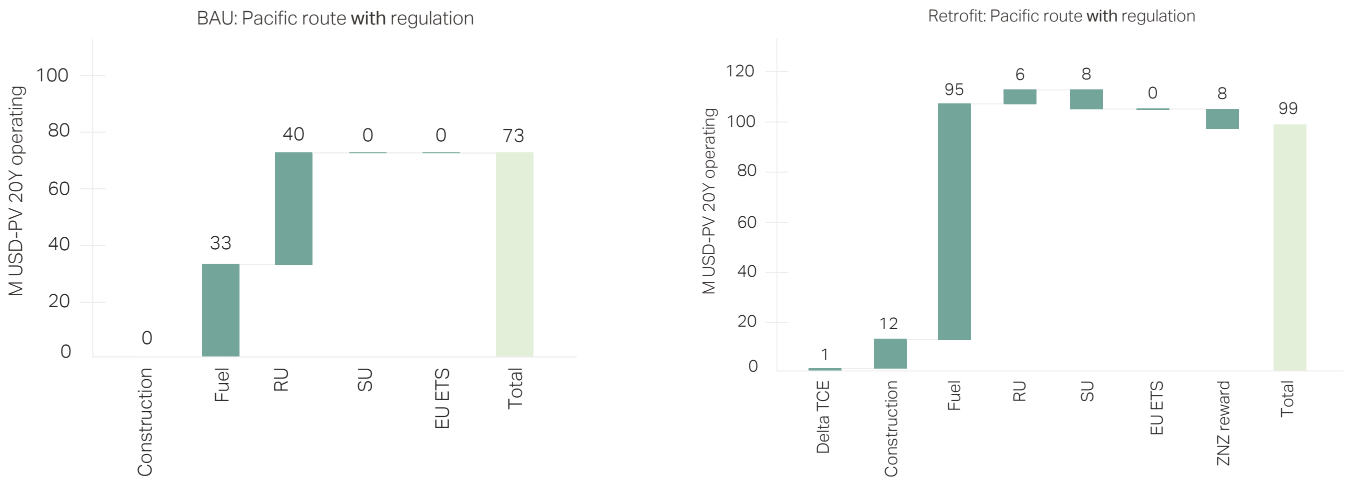


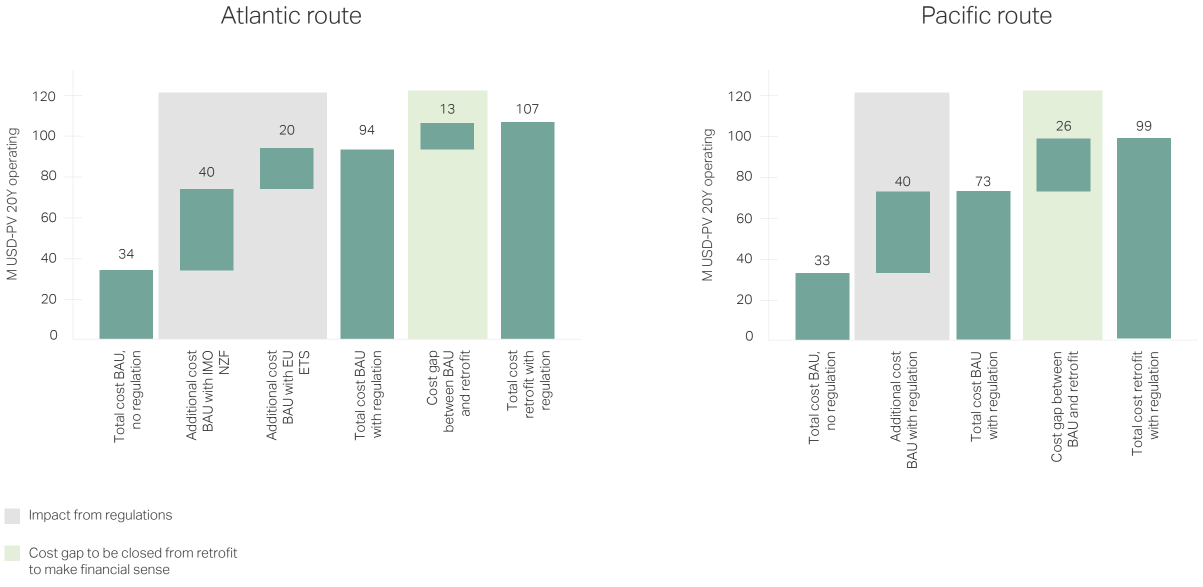
Figure 25: Cost gap for Scenario 1 (BAU) versus Scenario 2 (methanol retrofit) for the Pacific route (with regulation).



In both trade cases, our analysis suggests that the implementation of new regulatory regimes substantially increases the incentive to retrofit a vessel to methanol. With our regulatory assumptions in place, the cost gap between retrofitting and BAU is reduced by 43-57%. However, looking at the discounted cash flow calculations, we can also see that the BAU scenario still has a positive financial impact compared to the retrofit scenario for both trade cases – even when considering the impact of the regulations (Figure 26).

BAU = business as usual, RU = Remedial Unit, SU = Surplus Unit, EU ETS = EU Emissions Trading System, ZNZ = zero- or near-zero-emissions

Figure 26: Business case cash flow comparison of Scenario 1 (BAU) and Scenario 2 (methanol retrofit) on a 20-year time horizon.

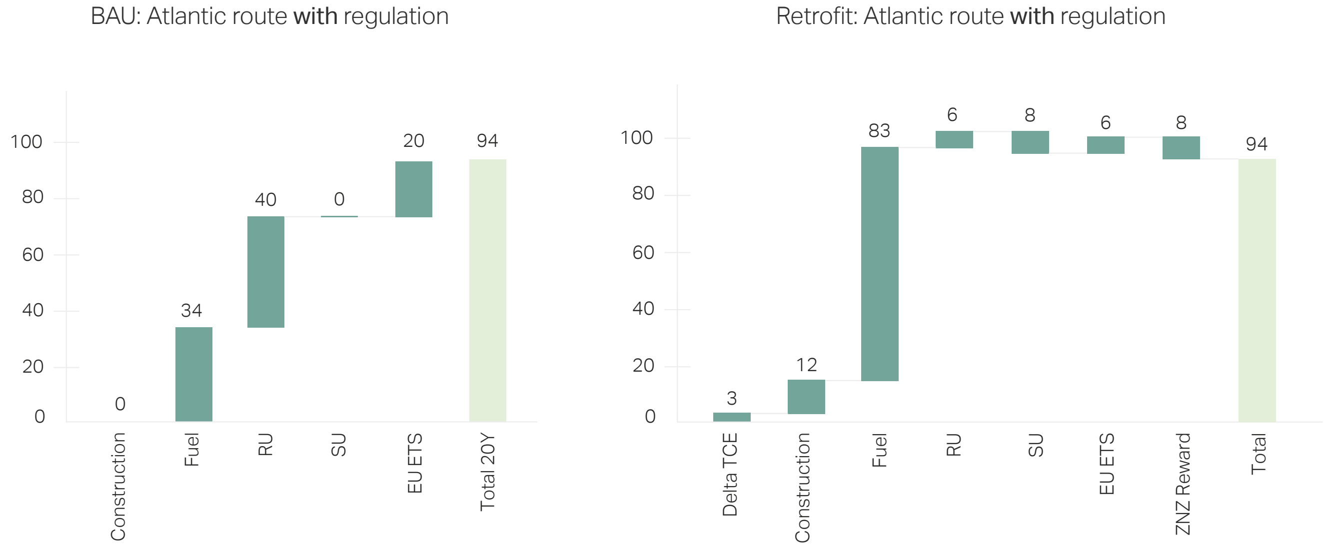


Therefore, we carried out a sensitivity analysis to establish what the price of bio-methanol should be for an investment of this magnitude to break even after twenty years of operating a converted bulk carrier. Figure 27 shows the results of our calculation.

BAU = business as usual, EU ETS = EU Emissions Trading System, IMO NZF = IMO Net-Zero Framework

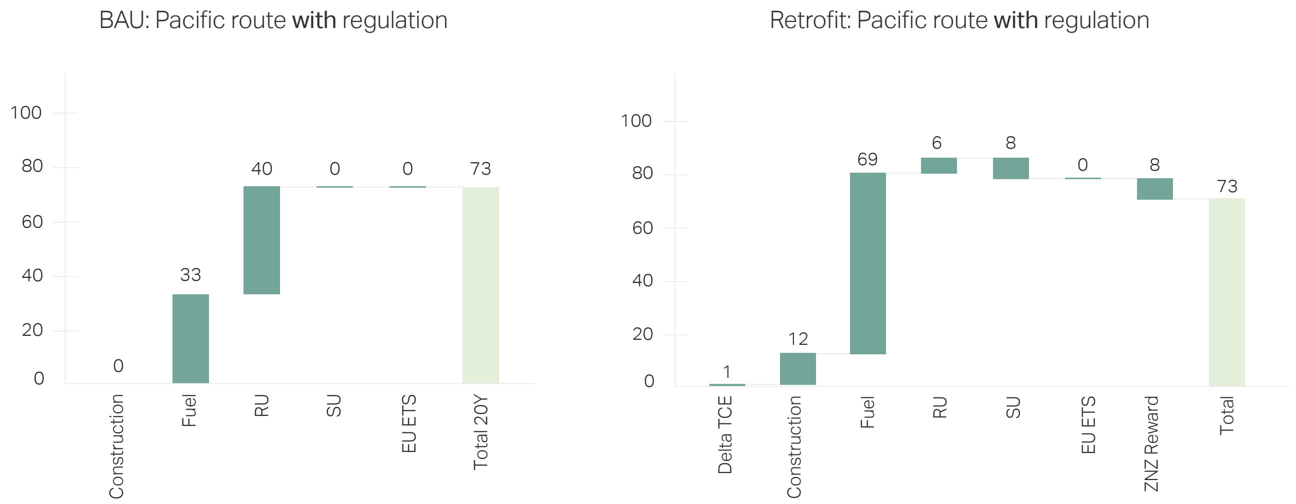
Figure 27: Modeled break-even for methanol price after 20 years.

MeOH price to break even in 20 years = 904 USD/ton


BAU: Atlantic route **with** regulation

Retrofit: Atlantic route **with** regulation

MeOH price to break even in 20 years = 743 USD/ton


BAU: Pacific route **with** regulation

Retrofit: Pacific route **with** regulation

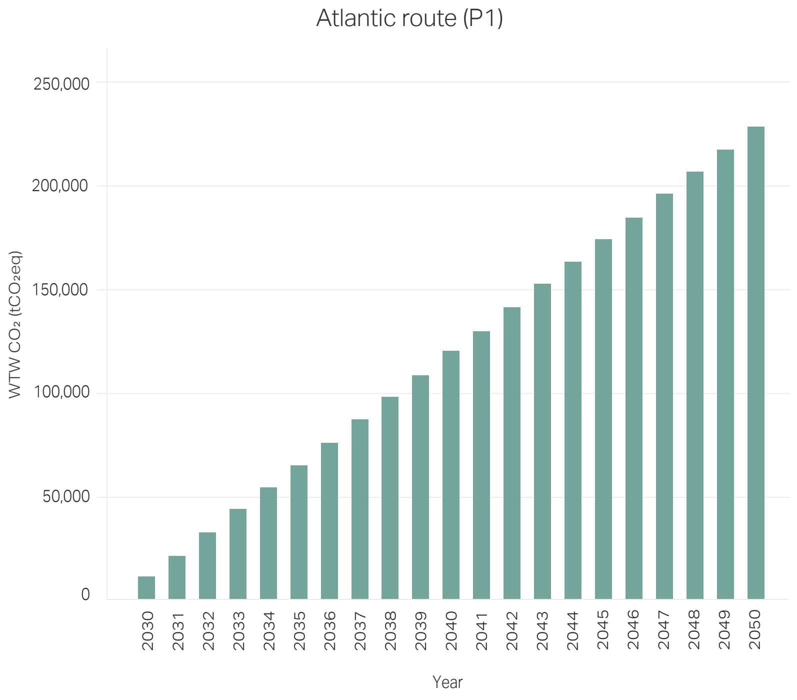
Depending on the vessel's trade route, it is fair to conclude that if the bio-methanol price drops to 743–904 USD/tonne, then a methanol retrofit can break even by the end of the asset's lifetime. For the sake of these calculations, we did not assume a different charter rate for vessels using a sustainable fuel option. The results could be impacted if vessels operating on sustainable fuels can command different charter rates.

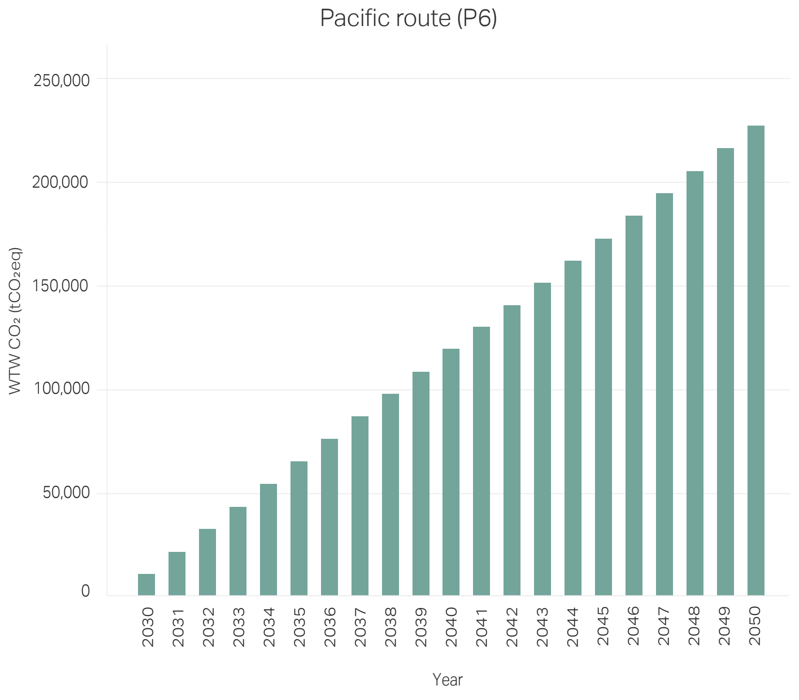
RU = remedial unit, SU = surplus unit, EU ETS = EU Emissions Trading System, TCE = time charter equivalent, ZNZ = zero- or near-zero-emissions

7.2.4 Cumulative GHG emissions reduction study

Figure 28 shows the difference between cumulative GHG emissions from 2030 to 2050 for the Atlantic and Pacific trades. The results for both voyage routes are almost the same. The total difference is around 220,000 t-WTW CO_2eq over 20 years (2030-2050).

Figure 28: Modeled emissions saved by bio-methanol operation on the Atlantic and Pacific routes.





WTW = well-to-wake

08 Conclusions and remaining challenges

When it comes to technical viability, nothing prevents a Kamsarmax bulk carrier from being retrofitted for methanol operation. The technical viability of the retrofit solution presented in this report was confirmed through continuous review by the project partners. These partners included Class NK, which is the classification society in charge of issuing the relevant Approval in Principle.

We studied several tank arrangement options for this project. Considering methanol's energy density and the endurance needed for a Kamsarmax vessel to avoid constant refueling, the most feasible solution for this study was to arrange the fuel tanks within the cargo hold. An on-deck tank with a large capacity is difficult to apply and would require large-scale retrofit work. Accordingly, the tank arrangement should not only be determined by the space available, but should also include additional calculations regarding e.g., structural and stability limitations, cargo loss limitations, retrofit complications impacting cost, operational restrictions, and time spent in the yard.

The retrofit package for this study was designed using principles of simplicity. Notably, the package implements ideas to reduce the retrofit workload, such as offline production modularity and methanol tank separation to enable passage through the hatch opening.

The shortest necessary construction period for converting an existing vessel of this type to methanol fuel is approximately 75 days. This is significantly shorter than the construction time required to build a new methanol-fueled vessel. Therefore, retrofitting can be a practical and timely solution to enable the use of methanol as fuel if newbuilding slot availability is a challenge. Importantly, the lead time for the engine components is currently around 1.5 years, which could significantly impact the execution of the retrofit work.

The design's viability was also checked in a full HAZID workshop, which identified relevant solutions, risks, and mitigations. This eventually led to an Approval in Principle by Class NK.

Having solidified the technical viability of the solutions, we conducted two main economic analyses. The first analysis sought to identify the CapEx of the retrofit, while the second undertook a 20-year financial modeling of retrofitting an existing bulk carrier and operating the vessel until end-of-life. The main insights from these analyses are:

- The biggest CapEx cost driver of the conversion is the cost of converting the main engine and support systems to methanol.
- CapEx delta and offline loss for the retrofit itself are estimated at around 25-30% of the newbuilding price of a single-fuel bulk carrier.
- The additional cost of running on bio-methanol compared to HFO is a major OpEx cost driver for this conversion.

Our second economic analysis examined the discounted cash flow from a 20-year perspective, accounting for the impact from EU ETS and the IMO NZF. At first glance, such regulations are a good start for reducing the relevant cost gap (by 43-57% in our calculations). This analysis is based on multiple assumptions, including future fuel prices, RU price, SU price, ZNZ reward, GFI reduction factors, and EU ETS cost.

However, even with the regulations in place, the business case for retrofitting appears to hinge on the price of bio-methanol. As such, we also carried out a sensitivity analysis on bio-methanol price. This analysis suggested that a retrofit investment could break even at the end of the vessel's operational life with a bio-methanol fuel price of 743-904 USD/tonne, depending on the trade route. Converting a vessel to dual-fuel capability provides shipowners and operators with the flexibility to choose the most economical fuel option among HFO, biodiesel, and bio-methanol, depending on market conditions.

Finally, we calculated the potential GHG emissions reductions from undertaking a retrofit as described in this study. By changing fuel to bio-methanol, the vessel can save about 220,000 t-WTW CO_2eq over 20 years – substantially reducing its emissions.

09 Project team

This document was prepared by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) in collaboration with our partners. Team members marked with an asterisk (*) were seconded to the MMMCZCS from their home organizations. All secondees and external contributors participated in a research capacity as part of the collaborative project and contributed technical input to the study.

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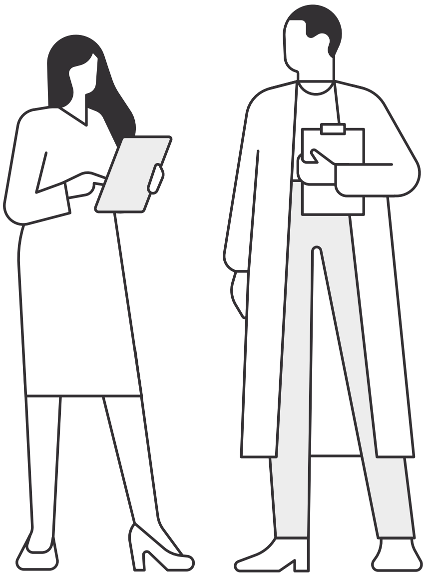

Abbreviations

AiP	Approval in principle
BAU	Business as usual
BC	Bulk carrier
CapEx	Capital expenditure
DWT	Deadweight tonnage
ECA	Emission control area
EU ETS	European Union Emissions Trading System
FBIVM	Fuel booster injection valve for methanol
FIV	Fuel injection valve
FPR	Fuel preparation room
FVT	Fuel valve train
GFI	Greenhouse gas fuel intensity
GHG	Greenhouse gas
HAZID	Hazard identification
HFO	Heavy fuel oil
IGF CODE	International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels
IMO	International Maritime Organization
IMO NZF	IMO Net-Zero Framework
LFSS	Low-flashpoint fuel supply system
LSFO	Low-sulfur fuel oil
MEPC	Marine Environment Protection Committee
MGO	Marine gas oil
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
MSC	Maritime Safety Committee
NM	Nautical mile
OpEx	Operating expenses
RU	Remedial Unit
SU	Surplus Unit
TTW	Tank-to-wake
TCS	Tank connection space
TCE	Time charter equivalent
WTW	Well-to-wake
ZNZ	Zero- or near-zero-emissions

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Appendix A: HAZID details

Table 15: Main hazards (moderate risk level) identified during HAZID workshop.

System	Hazards	Causes	Consequences
Storage tank	- MeOH leak (to TCS) - MeOH leak (to cofferdam) - MeOH leak (to pump room) - Air intrusion into tank	- Damage on tank boundary (storage tank) - Leak from piping/equipment in TCS (pipes, flanges, valves, etc.) - Damage to tank boundary (air from tank boundary) - Damage on attached piping (air from attached piping)	- Flammable atmosphere in TCS > fire/explosion > human fatality/human injury/damage to ship - Toxic atmosphere in TCS > human fatality/human injury - Flammable/toxic atmosphere on deck (around air outlets)
Fuel preparation room	- MeOH leak (local)	- Leak from piping/equipment in FPR (pipes, flanges, valves, etc.) - Leak from tank (damage on service tank) - Leak from tank (damage on drain tank) - Leak from drip trays (MeOH drain backflow from drip tray beneath MeOH supply unit)	- Flammable atmosphere in FPR > fire/explosion > human fatality/human injury/damage to ship - Toxic atmosphere in FPR > human fatality/human injury - Flammable/toxic atmosphere on deck (around air outlets)
Vent mast	- MeOH vapor released from tanks in FPR (service tank/ return chamber/ drain tank)	- High pressure in tank	- Gas flow to accommodation spaces > Flammable/ toxic atmosphere > human fatality/human injury/ damage to ship - Gas flow to people on exposed deck > flammable/ toxic atmosphere > human injury - Gas flow to lifeboat > emergency escape failed - Gas flow to emergency generator room > emergency generator cannot be used
Bunkering	- Overpressure of methanol fuel tank	- Improper filling rate - Blockage of pressure relief valve - N_2 supply system failure	- MeOH leak to open deck > flammable atmosphere on deck > fire/toxic atmosphere on deck > human injury - Damage to ship
Fuel supply system	- Negative pressure during fuel discharging	- Improper discharging rate - Blockage of vacuum relief valve - N_2 supply system failure	- Damage on tank boundary (storage tank) > MeOH leak to TCS/cofferdam/pump room > air intrusion into tank > flammable atmosphere in tank

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MeOH = methanol, TCS = tank connection space, FPR = fuel preparation room, N_2 = nitrogen, ESD = emergency shutdown device, M/E = main engine, LFSS = low-flashpoint fuel supply system, E/R = engine room

Electrical system	- Blackout – no power supply to MeOH-related equipment	- Generator failure - Electrical system failure	- ESD activation > -1. MeOH sealed in M/E > high pressure in pipe > pipe rupture > MeOH leak > fire/explosion > human fatality/human injury/damage to ship - Toxic atmosphere > human fatality/human injury -2. MeOH sealed in LFSS > Do - MeOH sealed in fuel transfer line (from fuel tanks to service tank) > Do - MeOH sealed in bunkering line > Do
Fire detection and protection system	- Fire in engine room	- Ship fire	- Emergency shut down > liquid seal (MeOH) in fuel pipe > high pressure > pipe rupture > escalation of fire/explosion
Lifesaving and evacuation system	- Lifeboat operations restricted	- Fire in MeOH module > access to/operation at muster station is restricted - Explosion in MeOH module > damage to lifeboat	- Emergency escape failed > human injury/fatality
Bunkering	- Lightning strike	- Operation/navigation in bad weather	- Lightning strike during bunkering/fuel discharging > fuel pipe damage and ignition by lightning > fire/explosion > human injury/damage to ship
Daily inspection / maintenance	- Human entry to spaces (FPR/TCS/pump room) with MeOH during daily inspection/maintenance	- C1. Local MeOH leak before maintenance 1. Leak from storage tank (to TCS/cofferdam/pump room) 2. Leak in FPR 3. Leak in E/R - Residual MeOH in tank 1. Inerting failed - Improper ventilation 1. Limited openings between the spaces in FPR	- Human exposure to MeOH > human fatality/injury

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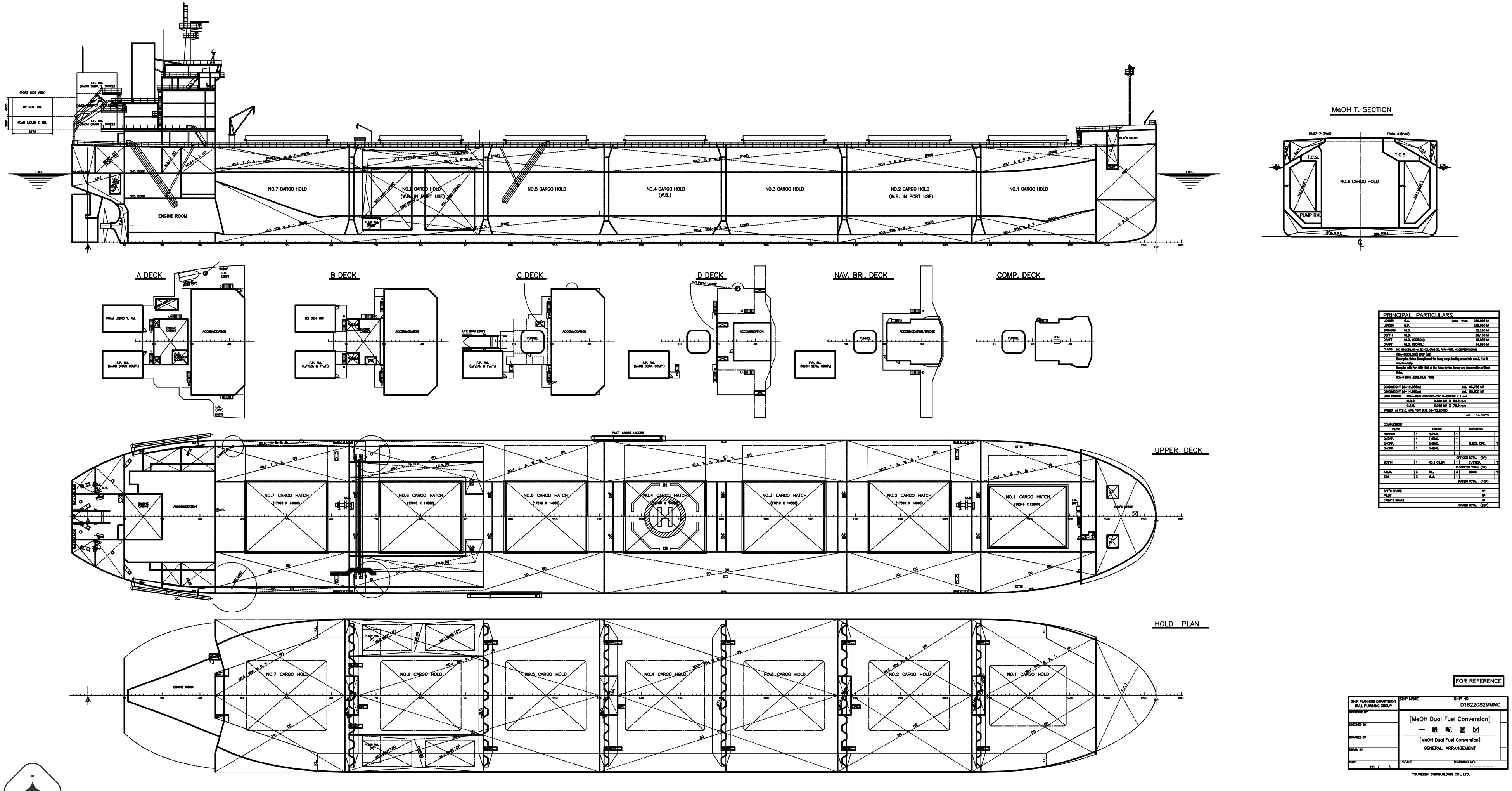
MeOH = methanol, TCS = tank connection space, FPR = fuel preparation room, N_2 = nitrogen, ESD = emergency shutdown device, M/E = main engine, LFSS = low-flashpoint fuel supply system, E/R = engine room, Do = ditto

Appendix B: General arrangement

Figure 29: General arrangement of an 82BC with methanol dual-fuel conversion.



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