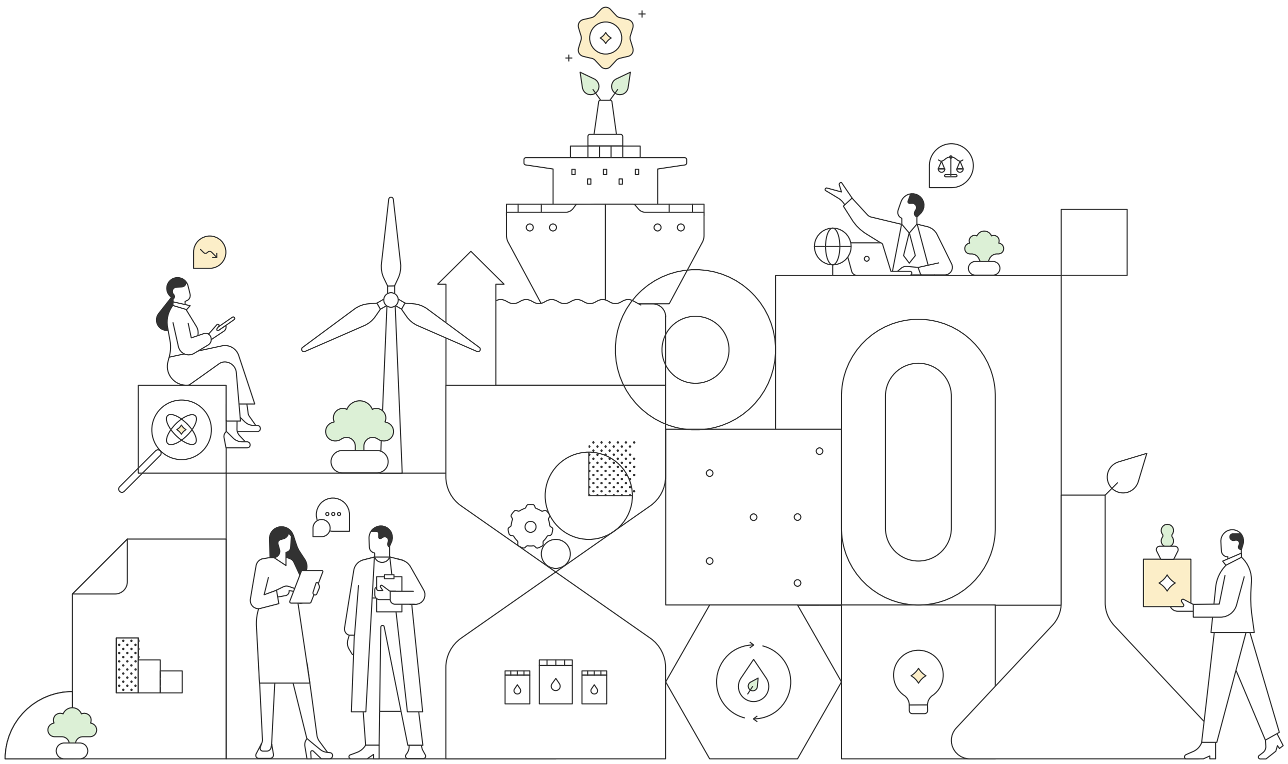
Preparing Container Vessels for Conversion to Green Fuels

A technical, environmental, and techno-economic analysis of the impacts of preparation and conversion

September 2022



Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

1 Introduction

This project report outlines our technical, economical, and environmental analysis of preparing container vessels for conversion to alternative fuels. Read on to learn the technical requirements for ammonia and methanol conversions, how to prepare vessels for later conversions, the total costs of conversion, and how conversion timelines influence total costs. We hope this information will help you plan your fleet decarbonization, so you can play your part in reaching zero by 2050.

Decarbonizing the maritime industry by 2050 demands a dramatic, industry-wide transformation. Shipowners will play a central role in the path to zero, and many have already committed to ambitious decarbonization strategies.[1] Transitioning from fossil fuels to green alternatives will undoubtedly be critical for decarbonization.

The future fuel landscape remains uncertain, but our analyses suggest it will probably involve a mix of fuels, including methanol and ammonia.[2] Despite the uncertainty, several shipowners have identified ammonia or methanol as key fuels in their decarbonization strategies. As a result, in recent months, there has been a flurry of news reports about companies ordering dual fuel or conversion-ready vessels in preparation for the switch to their future fuel of choice.

As the path to zero continues to develop, if you are a shipowner, you are probably facing an increasing set of dilemmas: Should you invest now in dual fuel new builds that can run on both traditional and alternative fuels? Are conversion-ready vessels with lower up-front costs a better option? How ready should a conversion-ready vessel be? Or should they stick with conventional vessel designs and hope to convert later when the landscape is more certain?

Converting traditional vessels to alternative fuels such as methanol or ammonia is a challenging project that demands significant investment. There are a vast number of technical and regulatory considerations. For example, retrofitting requires modification of existing structures and installations that are difficult to access in a finished vessel. It is certainly not as simple as adding an additional tank to carry the alternative fuel.

Dual fuel newbuilds are an attractive option to reduce the costs and complexity of later conversions. However, they require more upfront investment that may not pay off if the desired future fuel does not become as widely available as expected. What's more, the lower density of methanol and ammonia compared with fuel oil means they require large, additional tanks, which will remain unused until the new fuel is widely available. In container ships, there is no deck space for additional fuel tanks, alternative fuel tanks take up space used for containers and reduce the vessel's potential earning capacity, making a dual fuel vessel even riskier.

You may consider de-risking your investment by building intelligently designed conversion-ready vessels with a lower degree of readiness than a full dual fuel vessel, for example, with space allocated for future installations or key steel construction elements included. This reduces the initial investment and the impact on cargo space but introduces conversion costs later. However, it is still challenging to know whether this is a worthwhile investment and what level of readiness makes economic sense.

We assembled a team of partners from across the value chain to address some of these questions. This report outlines the results of this project. Here we focus on the results of investigations concerning container ships. We also explored the conversion of bulkers and tankers, the results of which we will publish in separate reports on the Center website.

[1] Ready, set, decarbonize! Are shipowners committed to a net zero future?, Mærsk Mc-Kinney Møller Center, 2022 https://www.zerocarbonshipping.com/publications/ready-set-decarbonize-are-shipowners-committed-to-a-net-zero-future/

[2] Position Paper Fuel Option Scenarios. Mærsk Mc-Kinney Møller Center, 2021. https://cms.zerocarbonshipping.com/media/uploads/documents/Fuel-Options-Position-Paper_Oct-2021_final_2022-06-07-102920_edoy.pdf

2 About this project

The objective of this project is to assess the technical, economic, and environmental consequences of converting container ships from fossil-based fuels to green fuel solutions; and recommend preparation levels for conversion-ready newbuilds that facilitate their transition and reduce future costs.

The project was a collaboration between the Mærsk Mc-Kinney Møller Center, and its Strategic Partners: ABS, Maersk, MAN-ES, Mitsui, MHI, NYK Line, TotalEnergies, and Seaspan.

In this project, we considered the technical and regulatory requirements for dual fuel ships. Based on this knowledge and the experience of the project partners, we proposed designs for full and reduced range newbuilds with varying degrees of preparation for later conversion, ranging from no preparation to full dual fuel vessels.

For each proposed design, we conducted a techno-economic assessment, investigating the total costs associated with each vessel including expenses associated with newbuilding, conversion, and lost cargo capacity. We analyzed the costs depending on conversion timelines, enabling us to provide recommendations for newbuild preparation levels for each scenario based on expected conversion times and the lowest total cost. Finally, we assessed the environmental impact of conversion by projecting the total lifetime emissions of converted vessels.

We used a 15 000 twenty-foot equivalent unit (TEU) container vessel with a twin island as a reference vessel for our designs (Figure 1). This is a typical "work horse" vessel that operates on many trade routes and has a relatively high fuel consumption, making it an attractive option for investments intended to reduce CO_2 emissions.

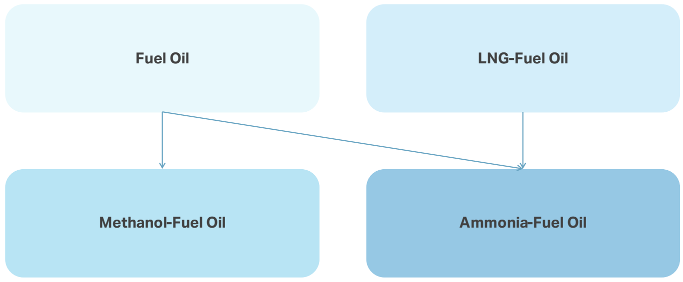


Figure 2: Conversion pathways analyzed in this project.

LNG = liquefied natural gas.

The desired range of a container vessel depends on the specific trade route it will use. The typical range of a 15 000 TEU container vessel is around 22 500 nm, which requires around 6 000 m^3 of fuel oil. To provide maximum trading flexibility, our full range designs provide the same full range with the alternative fuel. However, when retrofitting for operation on alternative fuels, a shorter range may be a good option to reduce tank sizes and minimize cargo losses, if trade routes and bunkering options allow. Therefore, we have also provided alternative, reduced range designs. For each conversion option, we have analyzed the impacts of conversion to both full range and reduced range. However, we expect ship owners to optimize the conversion scope to achieve maximum emissions reductions for their investment.

In this project we studied conversions of a 15 000 TEU container vessel from fuel oil to methanol or ammonia dual fuel, and from liquefied natural gas (LNG) to ammonia dual fuel. Although conversion from LNG to methanol is also a possibility, we have not included it in this study as market trends indicate that there is not much interest in this route, and it makes more sense to convert from LNG to ammonia as they are both gaseous fuels. We have not included conversion from fuel oil to LNG, as this has already been studied more widely and some conversions have been

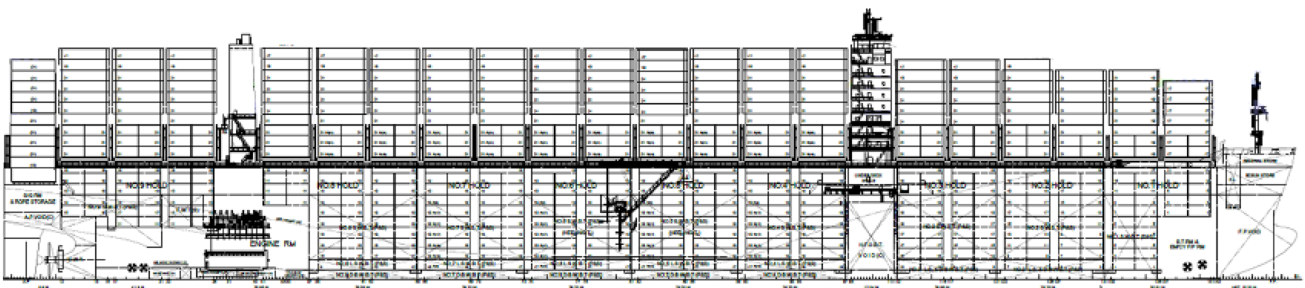


Figure 1: 15 000 TEU container vessel used as the reference vessel in this study.

made. Furthermore, we have not considered any conversions from liquefied petroleum gas (LPG), because there are currently no container vessels fueled by LPG. We have also excluded conversions to drop in fuels such as synthetic LNG on LNG fueled vessels or biodiesel on fuel oil vessels from this study as they do not require significant modifications or conversions. Furthermore, we have excluded conversion to hydrogen as an alternative fuel because the large volumes of hydrogen required make it a challenging solution for long range ocean going vessels.

2.1 Vessel preparation levels

Conversion-ready vessels can be built with varying levels of preparation for a later transition, but it can be difficult to know what level of readiness provides the best balance of reducing later conversion costs while limiting upfront costs and cargo losses. To solve this dilemma, in this report, we provide techno-economic assessments for vessels with four different preparation levels (Figure 3), ranging from traditional vessels with no preparation (Level 0) to dual fuel vessels fully capable of running on both fuel oil and an alternative fuel (Level 4). The proposed preparation levels are based on our assessment of what is relevant for reducing complexity during a future conversion. More detail about the preparation levels for each fuel conversion can be found in the later sections of this report.

2.2 Techno-economic assessment

Newbuild costs, conversion costs and cargo losses all vary with newbuild preparation levels and conversion timelines, making the total lifetime cost picture for conversions challenging to assess. To address this complexity, we provide an analysis of total cost (including the cost of lost cargo capacity) over the full lifetime of the vessel with different preparation levels and conversion timing since newbuild. To allow for easy comparison, the costs included in the assessment model are all present value (PV) and include:

- Add-on costs for preparing a dual fuel or conversion-ready vessel.
- Costs related to reduced cargo capacity in the period from newbuild **until** conversion or beginning to use the alternative fuel in the cases where tank installations are included when the vessel is built, and these installations have an impact on the cargo capacity.
- Costs related to reduced cargo capacity **after** the conversion and for the rest of vessel lifetime.
- Costs associated with the future conversion. (Excluding off-service costs)
- Assumed fuel cost savings related to operation on LNG before conversion. (LNG to ammonia conversion only)[3]

The total costs are calculated for each year from newbuild until the end of the vessel's lifetime. The total costs (Capital Expenditure (CapEx) and cargo loss value) for all preparation levels can be compared year by year. An interest rate of 7% is used, but inflation is not included in the calculations. Re-sale values, OPEX related to future methanol and ammonia processing, and carbon tax schemes are not included in this study, as there is a large degree of uncertainty around these factors.

As running vessels on LNG prior to conversion is assumed to provide savings in fuel costs compared with operating

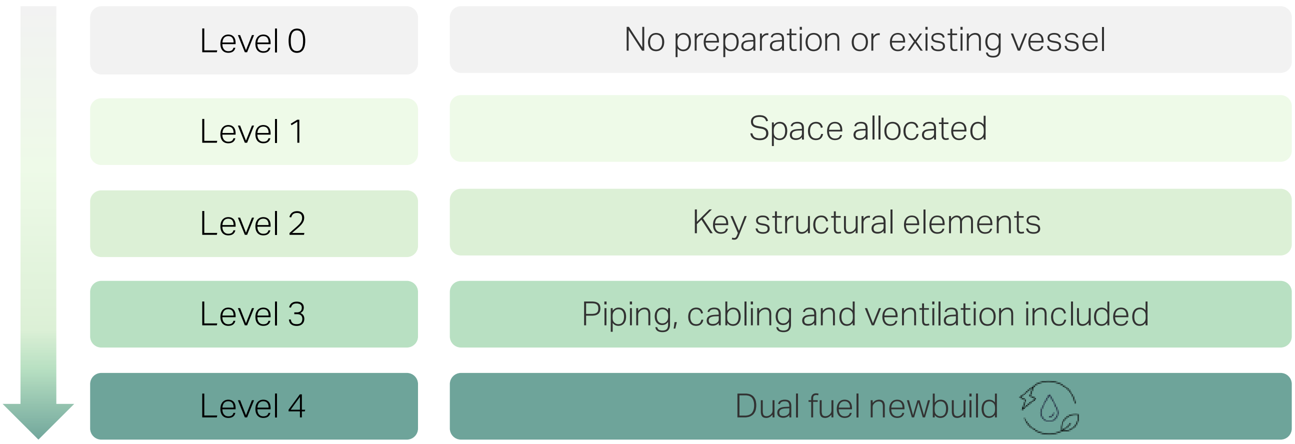


Figure 3: Newbuild preparation levels for future conversion.

[3] The fuel spread between fuel oil and LNG is assumed to be 140 USD/ ton fuel oil equivalent. This is based on resent figures in a normal fuel market. (Before COVID and sanctions against Russia)

on fuel oil, we have included these savings in our total cost assessment of LNG-ammonia conversions. Fuel cost savings are assumed to be 140 USD/ ton fuel oil equivalent (based on Center NavigaTE fuel costs).

2.2.1 Newbuild and conversion costs

Newbuild and conversion cost estimations are based on the experience and insight of the project participants. A 15 000 TEU fuel oil newbuild price is assumed to cost 150 million (mil.) U.S. Dollars (USD) and an LNG newbuild is assumed to be 174 mil. USD. The new build price is very market dependent, and this price may not reflect the current market situation. The cost of an ammonia dual fuel newbuild is estimated to be in the same range as LNG newbuild. The major cost items and origins of the data used in the techno-economic assessment are listed in Table 1.

Table 1: Cost estimation sources.

Cost	Cost based on
Main engine, auxiliary engine, and boiler conversion	Provided by project partners
Tank cost	Market insights from project partners and calculations based on tank size, steel, and manpower cost assumptions
Coating methanol tanks	Insight from project partners
Fuel supply systems	Indications provided by supplier
Yard installation	Experience of project partners

The model assumes that procurement of components and equipment, (pumps, compressors etc.) is done at the time of conversion to minimize the upfront investment. The off-hire cost associated with conversion is not included, as this depends a lot on current market situation. However, we have illustrated the potential impacts of off-hire costs using a sensitivity analysis.

The actual conversion price will depend on the geographic location and specific yard where the conversion is completed. Material prices, market situations, yard contingency levels and commercial project models (turnkey, fixed price, cost+mark up or time-and-material) can all have a big impact on conversion prices.

Machinery systems, engines, boilers and supply systems for methanol and ammonia are still in development and must be matured for commercial application, especially for ammonia. Ammonia newbuild and conversion costs have been estimated based on comparable LNG and LPG vessels and expected cost differences for items such as tanks and fuel supply systems.

2.2.2 Costs associated with reduced cargo capacity

The actual cost of a lost slot (slot loss) depends on the type of container (reefer, heavy or light) and the trade. A trade with heavy containers may be less impacted by the reduced cargo space volume but impacted more by the deadweight reduction, whereas other trades with volume limitations will, to a higher extent, be impacted by the reduced cargo space. Furthermore, the vessels may not operate fully loaded and the slot loss impact could be smaller in such cases.

In the calculations presented here, the value of lost cargo capacity is considered as the replacement cost, meaning the additional cost of having the container transported on another vessel, and not lost revenue. This value can vary with vessel and trade, so we have also illustrated the effects of varying slot loss values with a sensitivity analysis.

2.3 Greenhouse gas emission study

As the purpose of switching to alternative fuels like methanol or ammonia is to reduce emissions and comply with future environmental regulations, it is essential to assess the climate impact of conversion. This study provides a comparative assessment of the emissions from the operational part of the vessel lifecycle before and after the conversion. However, it was outside the scope of this project to conduct a full life cycle analysis of a vessel, therefore secondary data on vessel construction and end-of-life was collected from the “Sailing towards Zero: a case study on the carbon footprint of maritime components” paper. The figures provide a rough comparison of impact of the various parts of the vessel’s lifecycle (see Table 2).

We have analyzed the emissions from operation using two timescales: conversion after five years and after ten years. We have chosen these time scales because methanol and ammonia are expected to be available in limited scale in five years from the time of writing, with wider availability following in ten years if critical levers, including a global carbon levy, are activated. The carbon factors used to calculate operational emissions in our analysis, along with their sources, are described in Table 3. For fuel oil, methanol, and ammonia vessels, we have only considered the impact of CO_2 emissions. For LNG vessels we have also included the impact of methane slip. We assumed that fuel oil (including pilot fuel) and LNG will be of fossil origin.

Table 2: Lifecycle emission estimates for converted ships.
GHG = greenhouse gas

	GHG intensity	Unit	Source
Ship manufacturing	5.10	tonCO_2e/tonLWT	Sailing Towards Zero "Case study on the Carbon footprint of maritime components" report
Ship conversion	0.17	tonCO_2e/tonLWT	Calculated from information in the BW Group 2020 Sustainability report
Ship recycling	-1.55	tonCO_2e/tonLWT	Sailing Towards Zero "Case study on the Carbon footprint of maritime components" report. Based on recycling a generic vessel.
Total impact of ship lifetime (all lines summed)	3.89	tonCO_2e/tonLWT	

Using the calorific values of the fuels, we estimated the annual alternative fuel consumption using the following formulas:

$$Cons\ (AF) = Cons\ (FO) \times \frac{LHV\ (FO)}{LHV\ (AF)} \times (1 - PF)$$

AF = Alternative Fuel, FO = LSFO, PF = Pilot Fuel share (in energy), Cons = Consumption, LHV = lower heating value. The pilot fuel consumption was calculated as a percentage of the fuel oil consumption. 5% was used for methanol and 8 % was used for ammonia.

Table 3: Emissions figures for the selected fuel types.

+ Although the IMO figures only consider CO_2, we have used their emissions factors (instead of the FuelEU values for instance) because they are widely used in the maritime industry and are currently the only global standard for shipping.

* For LNG, the methane slip contribution from main engine and auxiliary engines to the final GHG depends on the vessel configuration and performance and therefore, it is not possible to provide one final figure for this fuel.

ǂ Nitrous oxide emissions from ammonia engines are still under investigation and could impact the GHG emissions of ammonia vessels.

GHG = greenhouse gas, LNG = liquefied natural gas, LSFO = low sulfur fuel oil, TTW = tank-to-wake WTT= well-to-tank WTW= well-to-wake.

	GHG impact	Unit	Source
	Fossil LSFO		
LSFO WTT	0.677	tonCO_2e/ton	NavigaTE
LSFO TTW	3.151	tonCO_2/ton	IMO MEPC 73/19/add.1 annex 5 +
LSFO WTW	**3.828**	**tonCO_2e/ton**	
	Fossil LNG		
LNG WTT	0.850	tonCO_2e/ton	NavigaTE
LNG TTW (CO_2)	2.75	tonCO_2/ton	IMO MEPC 73/19/add.1 annex 5 +
LNG TTW (CH_4, 2-stroke high pressure)	0.052	tonCO_2e/ton	Methane Documentation for NavigaTE 1.0
LNG TTW (CH_4, 4-stroke low pressure)	0.594	tonCO_2e/ton	
LNG WTW *		**tonCO_2e/ton**	
	Bio- or e-methanol		
Methanol WTT	-1.375	tonCO_2e/ton	NavigaTE
Methanol TTW	1.375	tonCO_2/ton	IMO MEPC 73/19/add.1 annex 5 +
Methanol WTW	**0**	**tonCO_2e/ton**	
	e-ammonia		
Ammonia WTT	0	tonCO_2e/ton	NavigaTE
Ammonia TTW	0	tonCO_2/ton	Ammonia doesn't contain carbon
Ammonia WTW	**0ǂ**	**tonCO_2e/ton**	

3 Technical considerations for fuel conversions

The properties of alternative fuels such as methanol and ammonia are significantly different from traditional fuel oil. As a result, there are a range of technical details that must be carefully considered when planning a methanol or ammonia newbuild dual fuel vessel or conversion to dual fuel. For example, the lower energy density of methanol and ammonia mean that conversions require additional fuel storage space. There are also additional safety considerations and regulatory restrictions associated with handling toxic gases and low flash point fuels which must be considered when using ammonia and methanol.

The following sections summarize the key technical aspects that, based on learnings from the project, must be carefully considered when planning a conversion, as they may have a significant impact on feasibility and cost. These include regulatory requirements, bunker station location and installations, fuel storage systems, fuel preparation rooms, fuel supply systems, fuel piping, engine conversion, after treatment and certification, ventilation and venting systems, fire prevention and detection, toxicity, and hull design.

3.1 IMO and classification society requirements

In general, all aspects of ship design and conversion should be completed in compliance with the appropriate International Maritime Organization (IMO) and classification society guidelines and regulations.

Currently, there are no prescriptive rules for designing, building, and operating ships fueled by methanol or ammonia. However, International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code) applies. The IMO has also published interim guidelines for ensuring the safety of ships using methanol,[4] and work is ongoing to provide similar guide for ammonia, with updates to the IGF code[5] to include methanol and ammonia expected in future. Classification societies have provided guidelines for use of ammonia as fuel. However, the alternative design approach must be used, where design is approved by flag state and class, based on risk assessments. The technical recommendations in the following sections are based on the current IGF code, and the interim guidelines for methanol.

3.2 Bunker stations

When designing the bunker station, risks and safety requirements related to open or semi-enclosed bunker stations should be considered with reference to the relevant classification and IMO guidelines and rules. The location of the bunker station should minimize the risk of fuel exposure to accommodation areas in case of spillage during bunkering.

Other installations may also be required, including a vapor return line, forced ventilation (in case of semi-enclosed bunker station), gas sensors/leak detection, emergency shut down systems, firefighting, water spray systems and breakaway couplings. The hose coupling type must be considered as well as whether a bolted flange connection or a dry disconnect coupling should be used. Manifold valves and their associated outfitting and piping should be protected from container handling. Fresh water showers and eye wash stations for emergency usage should be located close to the bunker station.

3.3 Methanol storage systems

Methanol is a low flash point fuel; it is liquid at normal temperatures and can be stored in stainless steel tanks or structural steel tanks coated with zinc silicate. Protective cofferdams are required around the methanol tank, except for areas towards the sea, below the lowest possible water line.[6] Proper coating of the tanks with zinc silicate generally requires a flat surface, without sharp edges, so we recommend building the tank with external structure and flat surfaces inside the tank. Conversion of existing fuel oil tanks can be difficult as cleaning and surface preparation, including rounding edges, can prove extensive.

We assume that it is possible to prepare a fuel tank to contain both fuel oil and methanol from newbuild by applying zinc silicate coating and building the required cofferdams around the tank. The tank is in principle built for methanol, but it can be used for fuel oil until the conversion and shift to methanol is made.

[4] interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel, IMO, 2020 MSC.1-Circ.1621 - Interim Guidelines For The Safety Of ShipsUsing MethylEthyl Alcohol As Fuel (Secretariat) (2).pdf (imo.org)

[5] MSC.391(95), the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code), IMO, 2021.

[6] MSC 95/22/Add.1 IMO International Code of Safety for Ships Using Gases or Other Low Flashpoint Fuels, IMO, 2015.

During conversion, the tank must be cleaned, and it will probably be necessary to replace the transfer pumps, depending on the vessel preparation level before conversion. The zinc silicate coating in the bottom of the tank may also need some repair during the conversion, following water exposure in the bottom of the fuel tank.

The tank must be inerted at all times during operation and as a result, an inert gas system is required. The inert gas production equipment must be able to produce inert gas with an oxygen (O_2) level below 5% by volume. If a nitrogen generator or storage facilities are installed in a separate compartment outside of the engine room, the separate compartment must be fitted with an independent mechanical ventilation system providing six air changes per hour with a low oxygen alarm fitted.

3.4 Ammonia storage systems

Ammonia is a gas with a boiling point of -33°C so it can be stored in a refrigerated state in insulated structural tanks. Tank options include several tanks: IMO Type A (hereafter Type A), IMO Type B (Hereafter Type B), IMO Type C (hereafter Type C), and membrane tanks. We have summarized the important properties of these tanks in Table 4.

Type A tanks are self-supported, independent, non-pressurized tanks with a space-efficient prismatic design. Type A tanks require a full secondary barrier, however, the secondary barrier is not insulated. As a result, if the tank is used to store ammonia and there is a leak, the ammonia will evaporate. To use a Type A tank with ammonia, the secondary barrier must be equipped with a suitable pressure relief system as seen on LPG carriers, where a blow-off hatch is located on the open deck. The location of the blow-off hatch or similar pressure relief system must be carefully considered, due to the limited deck space on container vessels.

Type B tanks are self-supported, independent, non-pressurized tanks that are often spherical or prismatic in design (Figure 4A). Like Type A tanks, Type B are highly space efficient. Type B tanks use a partial secondary barrier which can be covered by drip trays to direct and contain leaks. The IGF code states that calculations must be provided to verify that any leak from the tank will be small and contained within the drip trays. It must also be possible to purge the drip trays.

Although Type A and Type B tanks are the most relevant tank choices for large container vessels that must carry large volumes of fuel, membrane tank systems are relevant when converting an LNG fueled ship to ammonia, though technology solutions for this conversion are still under development.

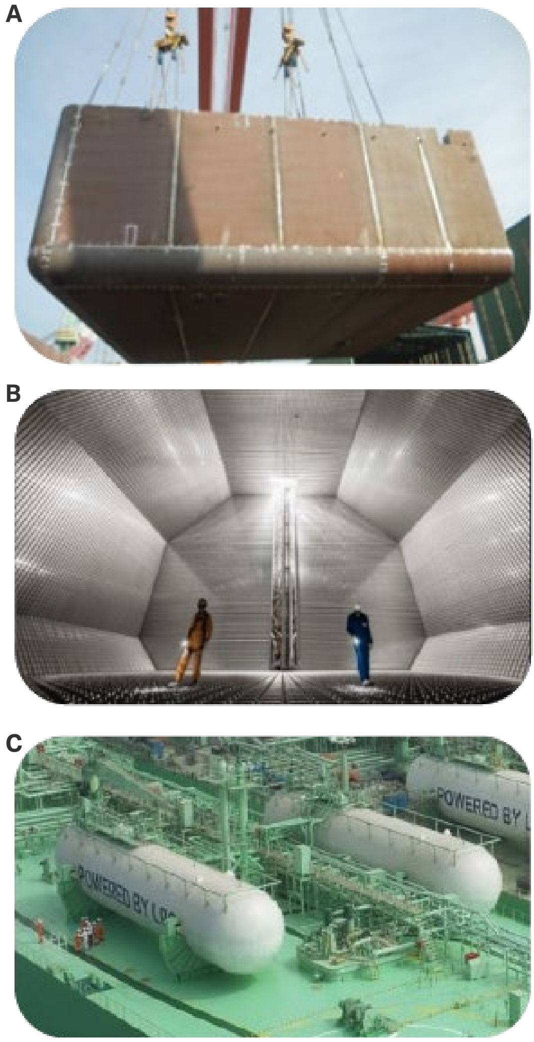


Figure 4: **A** - IMO Type B tank, (Source: Samsung Shipyard). **B** - Membrane tank (Source: GTT-Roland Mouron). **C** - IMO Type-C tank (Source: BWLPG).

Membrane tank (Figure 4B) storage systems are typically designed for atmospheric pressure/non pressurized LNG storage at -160°C. They are made of two layers of insulation and two tight barriers. Membrane systems are anchored to the ships inner hull structure, which acts as the supporting structure, and gives the best space utilization for high volumes. In tanks prepared for conversion from LNG to ammonia, the supporting structure will need to be able to act as a secondary barrier (low temperature steel) and at the highest readiness level, the tank shape and insulation foam density must be designed for the higher sloshing loads, expected for ammonia storage after conversion. An alternative, but not yet fully developed, solution is partly preparing the tank for ammonia. This would involve optimizing the tank shape for LNG use, applying the LNG related foam density, and preparing to install anti-sloshing devices at a later date.

Table 4: Summary of tank properties.

	Type A	Type B	Type C	Membrane
Space-Volume Efficiency	High		Low	High
Secondary Barrier	Required (Complete)	Required (Partial)	Not Required	Required (supporting steel structure)
Atmosphere control for fuel storage space	Inert gas or dry air	Inert gas or dry air	Dry air or no requirement if tank is heat insulated	Inert gas in insulation. (From LNG application)

For Type A, B and Membrane tanks, a reliquefication system or other means of tank pressure and boil off gas management is needed to maintain the storage temperature and pressure. For specific applications, membrane tank design pressures can be increased up to 1-2 barg.

Type C tanks (Figure 4C) are self-supported, independent tanks that can be used for storing ammonia. They are typically used for full or semi refrigerated storage and can be pressurized up to 18 bar. One option to prepare Type C tanks for conversion from LNG to ammonia is to use stainless steel as the tank material. If they are used to store ammonia in a fully or semi-refrigerated state, a reliquefication system or means of boil-off gas management will be needed to maintain the storage temperature. No secondary barrier is needed.

The disadvantages of the Type C tanks compared with Type A or B are the lower space efficiency and lower filling limits. Type C tanks could be a solution for smaller container feeders with shorter required ranges.

3.5 Tank pressure and boil off gas management

According to the IGF code, storing ammonia in non-fully pressurized tanks requires two independent means of managing the boil off gas to provide a redundancy system. This could either be two independent reliquification systems or one reliquification system combined with a boiler acting as a gas combustion unit or auxiliary engines burning ammonia gas.

3.6 Fuel tank location

The location of fuel tanks must be carefully considered in every newbuild and conversion design as it can be critical for vessel longitudinal strength, shear forces and local fatigue loads.

According to Section 5.3.3 of the IGF code, gas tanks such as those used to store ammonia should be the ship's breadth/5 or 11.5 m from the side shell, whichever is less. However, the IGF code also provides an alternative to this requirement in Section 5.3.4, where the designers use probabilistic approach criterion to calculate allowable locations (see Figure 5). This approach typically allows the tank arrangement to go closer to the side shell than the deterministic approach in Section 5.3.3 and is commonly used by shipyards and designers for LNG fuel tanks.

3.7 Fuel preparation room

The fuel preparation room contains all the relevant equipment for fuel preparation and supply purposes, such as fuel pumps, fuel valve trains, heat exchanges and filters. The location should be close to the main engine to reduce pipe distance as the fuel pipes must be purged when the engine either switches between fuels or is stopped. However, it must be separated from the engine room, although an entrance to the engine room via an air lock is a possibility. In case of converting to ammonia, the fuel preparation room houses equipment containing ammonia with only a single barrier, and in the design phase, escape routes and internal separation of equipment should be considered to reduce the risk of exposure in case of ammonia leaks. There are also special requirements for the ventilation system, and an external water curtain or spray system may be required.

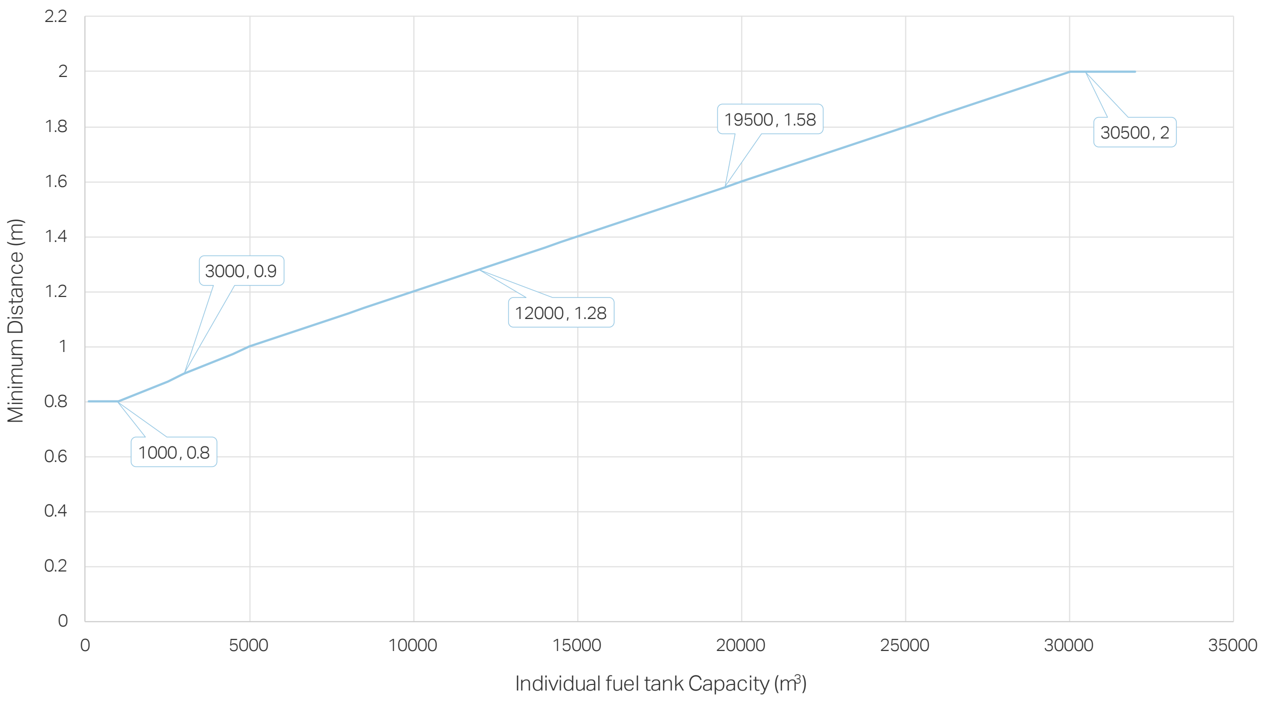


Figure 5: Minimum fuel tank distance from shell plate or aft terminal of ship calculated using the probabilistic approach.

3.8 Fuel supply system

A dedicated fuel supply system is needed for each fuel and must meet the requirements specified by the engine designer. The system supplies liquid ammonia or methanol to the main engine at the required pressure, around 80 bar for ammonia and 13 bar for methanol. Ammonia fuel supply systems for the auxiliary engines have not been developed yet but should be considered if the fuel supply system for the main and auxiliary engine can be combined/integrated.

3.9 Fuel piping

Fuel pipes outside the fuel preparation room in enclosed spaces must be double walled for transporting methanol and ammonia. The pipes will have to be routed in the existing ship structure and machinery space, which may make routing and access complicated.

When converting from LNG to ammonia, the double walled stainless-steel piping used for LNG could be prepared for ammonia as well, which would require adjusting the pipe diameter to allow for the larger volumes needed for ammonia.

3.10 Main engine, after treatment and certification

Conversion of the 2-stroke main engine, as a minimum, requires new cylinder covers, installation of methanol/ammonia injectors and a new, additional injection system with valve blocks and chain pipes. Other engine parts such as liners and exhaust valves may also need to be replaced, depending on the engine used in the conversion.

We also expect that ammonia fueled engines will require a high pressure selective catalytic reduction (SCR) system between the exhaust gas receiver and turbo charger to achieve NO_x Tier III operation and remove unburned ammonia. A high-pressure system should be used due to the relatively low exhaust temperatures when burning ammonia. If a conversion involves retrofitting an existing vessel that doesn't have an SCR system, one will need to be installed. However, this can be a challenge due to the large size of SCR reactors. Depending on the emission profile of ammonia fueled engines, additional catalysts may be needed to treat ammonia slip or nitrous oxide.

When using new fuels with existing engines, protype testing and NO_x certification may be required. Engine manufacturers typically conduct prototype testing on one or more engines from a family, with the aim verifying and optimizing the safety, performance, and emissions of the engines. The standards for these tests are internal, for example MAN-ES set criteria for heat load testing, temperature effects on the engine, exhaust valve burn away rate and other critical parameters. For conversions, if a prototype already exists for the engine with the new fuel, no further prototype testing is required. However, for a new fuel with an existing engine design (for example, the first 70-bore methanol engine design spec), a series of prototype tests should be carried out on testbed, or in-situ.

NO_x certification tests are a legal requirement for every engine released to market. They are designed to confirm NO_x emissions and ensure compliance with classification standards and regulations from other regulatory bodies. For retrofits, every parent engine requires post-retrofit NO_x testing for recertification. Provided that NO_x certification tests have been carried out on a parent engine of a particular design specification, NO_x testing on engines from the same family is not required.

3.11 Ventilation, purging ventilation and venting systems

Arrangement of ventilation exhaust outlets from the fuel preparation room and tank connection spaces should be designed to avoid potential exposure to personnel outside these areas.

The accommodation ventilation system should be designed for maintaining over pressure and may be equipped with gas sensors at the air inlets. In case of presence of gas, the system should switch to maximum rate of recirculation.

The location of the vent mast, connected to the pressure relief valves on the fuel tank(s), should be designed according to the rules and classification guidelines. The key requirements are related to a minimum distance from vent mast to accommodation and air intakes. When designing the tank ventilation for a methanol tank, the pipe must be self-draining to the tank to allow for the possibility of condensation.

3.12 Prevention, detection, prevention of propagation, and control of fires

Methanol and ammonia are both flammable, so fire prevention and control should be carefully considered when planning a dual fuel vessel or conversion .

According to the IGF code, to prevent fires the vessel should be split into safe zones and hazardous spaces (Zones 0 , 1 and 2) where gases are handled. Detailed definitions of the various zones are specified in the IGF code. Equipment used in Zones 0,1 or 2 must be explosion-proof. The IGF code also specifies where gas detectors and fire detectors must be installed to ensure fire detection. These areas include fuel preparation rooms, double pipes, air locks, and cofferdams.

To prevent propagation of fires, all spaces containing gas-related equipment are classified as Category A machinery spaces, with insulation requirements (A60 / A30 / A0 / B-) specified in SOLAS Reg II-2/9. To enable fire contol, bunker stations, fuel preparation rooms, tanks on open deck or superstructures, pumps rooms, etc. in the vicinity of the tanks should be sprayable with water, or in the case of methanol, alcohol resistant foam. Fixed fire fighting systems should also be installed in the fuel preparation room as specificed in the IGF code. In case of methanol, an approved alcohol-resistant foam system must also be installed, covering the tank top and bilge area under the floor plates.

3.13 Toxicity-related items

Both ammonia and methanol are toxic and, as a result the preliminary IMO interim guideline for methanol as fuel and classification guideline for ammonia as fuel have special requirements for protection of personnel. Showers and eye wash stations must be located close to areas where the possibility for accidental contact with fuel or gas leaks exists, for example at bunker stations. For ammonia, there are also additional measures for protection against gas leaks. Water curtains above the entrances to the fuel preparation room, water spray systems around the fuel preparation room and on the sides of the accommodation facing areas with a possible leak risk, such as the bunker station, fuel preparation room and tank connection space, must be considered.

3.14 Ship stability and hull

Installation of additional fuel tanks will have an impact on the stability and longitudinal strength of the vessel. For example, the size and location of fuel tanks will impact the vessel stability and may impose limitations to loading conditions. On a large container vessel, tanks will occupy space in the lower part of the ship where you would normally place heavy containers. The weight and volume of a tank will in principle replace weight and volume of containers, but fuel tanks are likely to be empty sometimes and this can cause increased shear forces to the hull that may impact stability and or limitations to loading of the vessel. Stability checks must be made with various tank and loading conditions to ensure stability is maintained

Furthermore, the hogging still water bending moment of the vessel will typically increase when additional tanks are installed due to the increased tank weight and the change of center of gravity of fuel. To ensure longitudinal strength, the hogging moment in alternative loading and severe departure conditions should be carefully studied with specific calculations for each vessel. If the original design does not have enough margin in hogging bending moment, reinforcement or limitation of loading conditions may be necessary. Retrofitting supporting structures for tank(s) to support both the weight and dynamic load of the fuel tanks during a conversion is time consuming and complex. As a result, the effects of additional tanks on longitudinal strength and stability should be considered from newbuild.

3.15 Major conversion designation and engine NO_x tier classification

In general, the major conversion clause is applicable to major ship changes such as cargo type, size, etc. Conversion of the vessel to an alternative fuel is, however, not considered as a major conversion if the vessel is not elongated.

For NOx purposes a dual-fuel conversion does not necessitate a NOx tier upgrade of an engine. As per MARPOL Annex VI Regulation 13 and the updated IMO NOx Technical Code 2008, a dual-fuel retrofit would be classified as a 'Substantial Modification', and 2.3.2. of MARPOL Annex VI Reg. 13 requires that the engine maintains the tier level as prescribed by the original date of construction of the vessel." The key consideration here is that the keel laying date remains the applicable NOx tier level unless the engine is replaced, or an additional engine is fitted.

4 Fuel oil to methanol conversions

In this section, we provide proposed designs for full range dual fuel vessels, and full range and reduced range vessels converted without preparation. Furthermore, we describe newbuild preparation levels specifically for conversion from fuel oil to methanol-fuel oil. Our proposed designs aim to minimize cargo loss and conversion complexity, while adhering to the regulations and other technical requirements outlined in Section 3.

We also provide a techno-economic analysis of the total costs of conversion depending on conversion timelines, desired range, and newbuild preparation levels. From the results of this analysis, we recommend newbuild preparation levels depending on the desired range when conversion is expected, allowing intelligent newbuild design and preparation for future fleet planning.

4.1 Proposed designs for methanol-fuel oil dual fuel and conversion-ready vessels

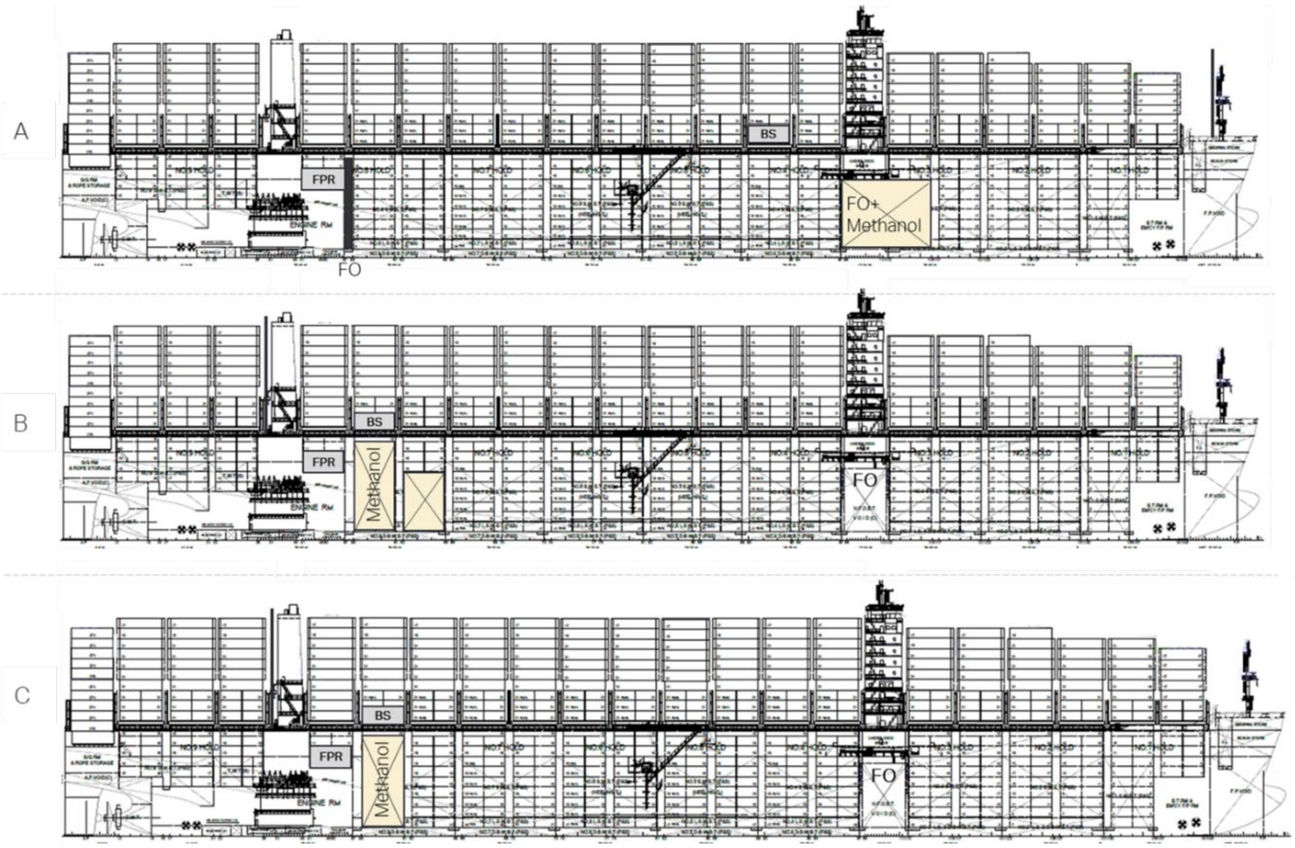


Figure 6: 1Designs for a 15 000 TEU container vessel for conversion from fuel oil to methanol. (A) Full range (16 000 m^3) dual fuel vessel (preparation level 4) or after conversion from newbuild preparation levels 1-3. (B) Full range (16 000 m^3) vessel after conversion from newbuild preparation levels 0. (C) Reduced range (10 000 m^3) vessel after conversion from newbuild preparation levels 0-3. FPR= fuel preparation room, FO=fuel oil, BS=bunker station.

4.1.1 Tank arrangement

We propose the same tank arrangement for dual fuel vessels and preparation levels 1-3,full range, with methanol tanks located in the same position as traditional fuel oil vessels (under the accommodation) using a combined fuel oil/methanol tank system, see Section 3.3. This reduces cargo losses compared to installing additional methanol tanks in the cargo area later. The combined fuel oil/methanol tank system should be divided into separate tanks for each fuel (see Section 3.3 for the tank requirements for methanol storage). Due to the combined tank concept, it is possible to store methanol in the same tank as fuel oil (after thorough cleaning and corrosion repair) so if full methanol range is not required from day one, it can be varied with the number of tank sections shifted to methanol. However, it should be noted that fuel oil and methanol cannot be stored with a single barrier between them, and the arrangement of the tank sections should include smaller tank sections that can be left empty, to act as a buffer zone between the methanol and fuel oil.

Additional tanks for fuel oil for dual fuel operation either at newbuild or after conversion can be built between the cargo holds, with their capacity determined by the required fuel oil range. In our dual fuel, full range design we have included a fuel oil tank in front of the engine room (see Figure 6A). In our full range design, the methanol tank capacity will be 16 000 m^3 and the slot loss will be around 240 TEU.

If a vessel is unprepared for conversion and the fuel tanks are not prepared for methanol (preparation level 0), for a full range conversion we propose locating the additional tank next to the engine room (see Figure 6B). It is assumed that the tank will be built as a self-supporting double walled tank, that will be fixed in the cargo hold, and not fully integrated in the hull structure. This is, however, heavy and inefficient in terms of space, with a slot loss of 610 TEU.

As an alternative solution, a single-walled tank could be built and integrated into the cargo hold, where the space between the tank and cargo hold will act as the required cofferdam. However, the installation and integration work for this solution will be more extensive compared to the double walled self-supporting tank.

In our reduced range design, we include a smaller methanol tank system that only occupies a single cargo bay, located in the cargo bay close to the engine room and fuel preparation room (see Figure 6C). In this design case the auxiliary engines and boiler are assumed not to be converted. This design provides a methanol tank capacity of approximately 10 000 m^3 and a slot loss of around 400 TEU.

4.1.2 Bunker station location

In our dual fuel and conversion-ready design proposals (Figure 6A), an open type or semi-enclosed bunker station is arranged at port and starboard side so that the parallel body line is sufficiently contacted with a bunker barge. It can be a challenge to arrange a bunker station in the cargo area, due to the limited space from the side of the ship to the hatch cover. The space between the hatch covers may be used, but width is limited. As a result, it is recommended to prepare for the future bunker station at newbuild stage.

In our unprepared conversion designs, or reduced range prepared, (Figure 6B and C), the bunker station is located just above the tank, providing the shortest possible bunker line. As an alternative, the bunker station could be located at the engine casing area, where more space is available.

4.1.3 Vent mast location

We propose locating the vent mast at the front of the vessel, with appropriate distance to the accommodation, service spaces, the funnel, air intakes, and ignition sources, which is ten meters according to the interim IMO guideline for using methanol as fuel. We assume that a location at the foremast or engine casing is feasible, but detailed study is needed to ensure a design with allowable pressure drop in the vent line is feasible. The vent mast could be located elsewhere, as the guide allows for the outlet to be located not less than three meters above the deck or gangway if located within four meters from such gangways.

4.2 Preparation levels for fuel oil to methanol conversion ready newbuilds

Based on the design proposals we have outlined above, and our assessment of which preparations will have the most impact on reducing complexity during a future conversion, we propose the below preparation levels for fuel oil to methanol conversion-ready newbuilds.

Table 5: Preparation level description (fuel oil to methanol conversions).

* In case of a newbuild that is not prepared (Preparation level 0), it is still relevant to make sure the main engine, and optionally the auxiliary engine and boiler can be converted later.

	Preparation level 1	Preparation level 2	Preparation level 3
Tank	Fuel oil tanks to be constructed for methanol with cofferdams and coated with zinc silicate to contain methanol later Tank capacity to be split to support dual fuel operation with both methanol and fuel oil		
Main Engine*	Engine type chosen to allow for later conversion		
Auxiliary engine and boiler*	Engine type chosen to allow for later conversion. Boiler sized for methanol and prepared for new burner		
Bunker station	Space allocated	Methanol connections to tanks established. Bunker line routing prepared (supports and trunks)	Full installation including: Manifold, bunker line, safety system, firefighting, ESD etc
Fuel supply system	System scope must be assessed to allow dimensioning of the fuel preparation room and allow space allocation		
Fuel preparation room	Space allocated	Room constructed	Power, safety systems and ventilation installed
Ventilation	Space allocated	Arrangement designed and duct supports installed.	Established. Ventilation ducts installed. Sensors and closing systems installed
Piping and electrical installations	Space allocated including possible extension of switchboards	Pipe supports, pipe and cable trunks made. Cable ladders and supports. Spare breaker and busbar installed	Piping, cabling, ventilation ducts installed
Vent mast	Space allocated	Support constructed.	Vent mast constructed.

4.3 Techno-economic analysis of fuel oil to methanol conversions

Table 6 shows the CapEx investments for newbuilding and converting each design and preparation level, presented as a percentage of the cost of a standard fuel oil newbuild vessel.

The cost of a full dual fuel newbuild is currently uncertain as no typical values exists. We have estimated the cost based on the assumption that the market has matured and is beyond "first mover" cost levels.

In Figure 7, we illustrate the total cost of conversion, including newbuilding CapEx, conversion CapEx, and the cost of lost cargo capacity before and after conversion.

Table 6:1 CapEx investments for newbuild and conversion of 15 000 TEU container vessel from fuel oil to methanol-fuel oil with varying preparation levels. A 15 000 TEU fuel oil newbuild price is assumed to be 150 Mil.

Full range					
	Preparation level 0 (% of newbuild cost)	Preparation level 1 (% of newbuild cost)	Preparation level 2 (% of newbuild cost)	Preparation level 3 (% of newbuild cost)	Preparation level 4 (% of newbuild cost)
Preparation cost at newbuild	0	2	3	4	11
Conversion cost	16	13	11	10	
Total CapEx	16	15	14	14	
Reduced range					
	Preparation level 0 (% of newbuild cost)	Preparation level 1 (% of newbuild cost)	Preparation level 2 (% of newbuild cost)	Preparation level 3 (% of newbuild cost)	Preparation level 4 (% of newbuild cost)
Preparation cost at newbuild	0	0.2	1	2	
Conversion cost	12	12	10	9	
Total CapEx	12	12	11	11	

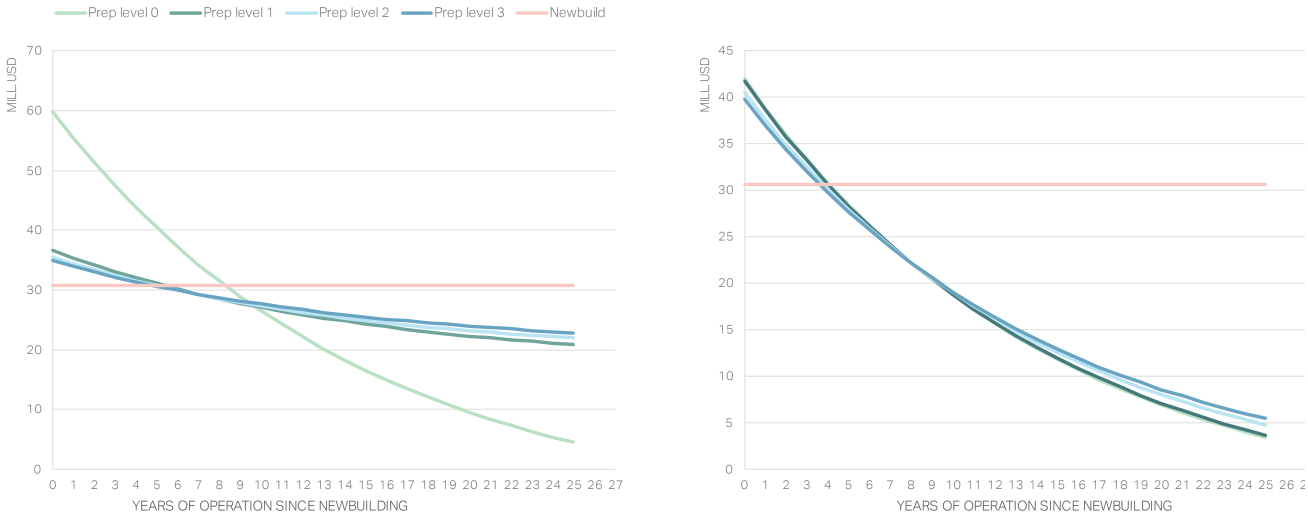


Figure 7: 2Present value of total conversion cost of a 15 000 TEU container vessel, fuel oil to methanol, full range (left) and reduced range (right).

Based on this analysis, we provide recommendations for newbuild preparation levels depending on the expected conversion timeline (see Table 7).

Our recommended preparation levels are based on the lowest total costs; however, ship owners should carefully consider what is right for them and their own individual circumstances when planning vessels and conversions.

As the graphs show, at short conversion timelines, dual fuel newbuilds are the most cost-effective option. At intermediate timelines, conversion-ready vessels (preparation levels 1-3) become the better option.

In this case, the larger tanks installed at newbuild stage have a negative impact on cargo capacity from delivery, but the effect is lessened after conversion compared with an unprepared vessel. There is minimal difference in the total costs associated with preparation level 1,2 and 3 in this period. Preparation level 1 results in the lowest newbuild costs, but a preparation level 3 may save time at conversion and could be beneficial if converting early.

For longer conversion timelines, a traditional, unprepared vessel is the best option with full cargo capacity maintained until conversion, but the lowest capacity after conversion. This solution is, therefore, more attractive the later the conversion is done. Total costs are significantly reduced by converting to a vessel with a reduced methanol range using a smaller tank and leaving the auxiliary engines and boiler unconverted. This strategy reduces newbuild CapEx by 3-4 % and significantly reduces slot loss costs. However, the reduced methanol range will require more frequent bunkering. Furthermore, the cost savings from converting the auxiliary engines and boiler should be balanced with the cost of burning compatible biodiesel to reduce emissions.

The value of the cargo loss can vary, impacting total costs. We conducted a sensitivity analysis to investigate the effects of varying slot loss values on the outcomes of our analysis. We found that while changing the slot loss values in the model impacts the total cost, it does not change our cost observations or recommendations

Off-hire costs are not included in our model but could impact conversion costs. Off-hire costs for a container vessel is very dependent on the market situation. In a sensitivity analysis, we found that for each one mil USD in off-hire costs that is added for a conversion, the break-even between a dual fuel newbuild and a conversion option is extended by one year, meaning that the dual fuel newbuild has the lowest cost for one year longer than presented above.

Table 7:2 Recommended preparation levels for fuel oil to methanol conversion-ready vessels based on scope and conversion timelines. PV= present value.

	Full range		
Years before methanol operation	0-5 years	5-10 years	10-25 years
Lowest PV cost option	Dual fuel newbuild	Preparation level 1,2 or 3	Preparation level 0
	Reduced range		
Years before methanol operation	0-3 years	3-8 years	8-25 years
Lowest PV cost option	Dual fuel newbuild	Preparation level 3	Preparation level 0 -1

4.4 GHG assessment (fuel oil to methanol conversion)

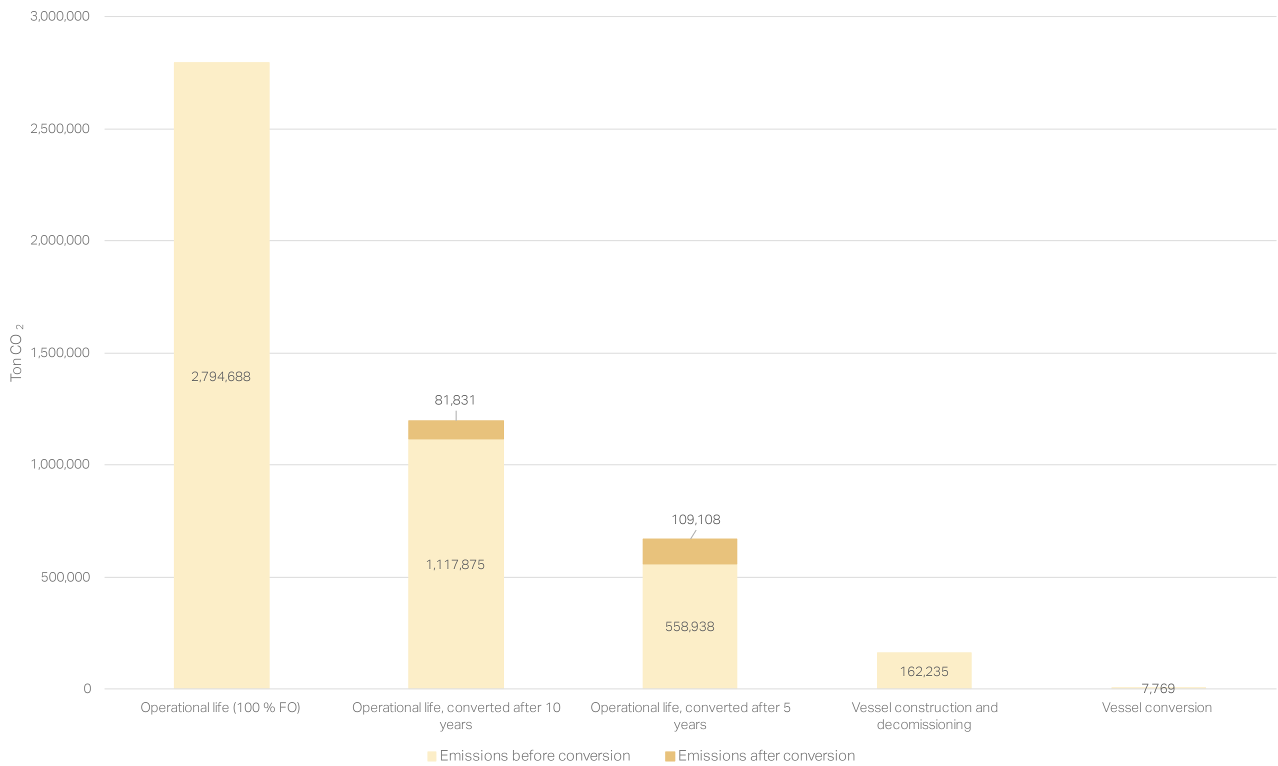


Figure 8: CO_2 emissions, 15 000 TEU container vessel, fuel oil to methanol conversions, full range and scope.

Figure 8 illustrates the total lifetime CO_2 emissions for vessels converted after five or ten years compared with a reference vessel operating on fuel oil for the lifetime of the vessel. This is based on a yearly total fuel consumption of 29 200 mt fuel oil and 25-year lifetime. Emissions after conversion are from the pilot fuel oil (5%) needed for main and auxiliary engines. In case a CO_2 neutral oil is used as pilot oil, the emissions after conversion can be considered as zero.

CO_2 emissions related to building and scraping a vessel, as well as conversion of the vessel are illustrated for comparison, showing that the emissions for the conversion are minimal compared to operational emissions.

5 Fuel oil to ammonia conversions

In this section, we provide proposed designs for full range dual fuel vessels, and full range and reduced range vessels converted without preparation. Furthermore, we describe newbuild preparation levels specifically for conversion from fuel oil to ammonia-fuel oil. Our proposed designs aim to minimize cargo loss and conversion complexity, while adhering to the regulations and other technical requirements outlines in Section 3.

We also provide a techno-economic analysis of the total CapEx of conversion depending on conversion timelines, desired range, and newbuild preparation levels. From the results of this analysis, we recommend newbuild preparation levels depending on when conversion is expected, allowing intelligent newbuild design and preparation for future fleet planning.

5.1 Proposed designs for ammonia-fuel oil dual fuel and conversion-ready vessels

5.1.1 Tank arrangement

Ammonia requires a larger tank volume than fuel oil (more than three times, net volume) for the same range. This, combined with the differences in storage requirements for fuel oil and ammonia mean it is not feasible to build vessels with fuel oil tanks that can be prepared for later use with ammonia, as we suggested in the case of methanol dual fuel and conversion-ready vessels.

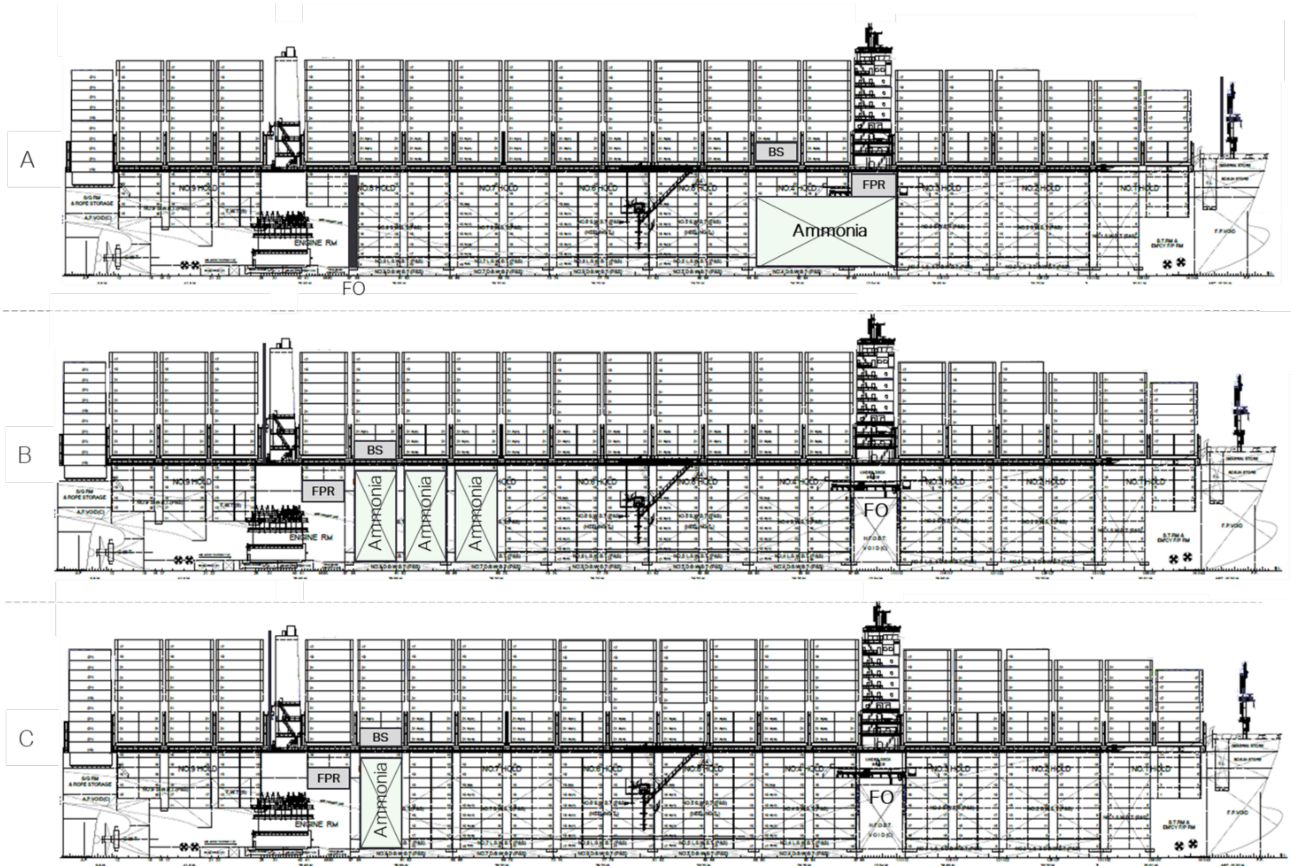


Figure 9:3 Designs for a 15 000 TEU container vessel for conversion from fuel oil to ammonia-fuel oil. (A) Full range (20 000 m^3) dual fuel vessel (preparation level 4). (B) Full range vessel after conversion from preparation level 0-3. (C) Reduced range (7 800 m^3) vessel after conversion from newbuild preparation levels 0-3. FPR= fuel preparation room, FO=fuel oil, BS=bunker station.

As a result, in preparation level 4, we propose storing the ammonia in a fully refrigerated, insulated IMO Type A or B tank located partly under the accommodation (Figure 9A), in the same layout as current LNG dual fuel vessels. The tank is assumed to be B/5 from the ship side to increase safety as the tank is under the accommodation.

We suggest locating the fuel oil tanks between the cargo holds with the number of tanks and dimensions determined by the required fuel oil range post conversion. With an ammonia tank capacity of 20 000m^3 this arrangement results in a slot loss of 540 TEU.

In preparation levels 0-3, ammonia tanks will have to be installed in the cargo area during conversion (Figure 9B). However, this results in a large loss in cargo capacity after conversion. If full range is required, three cargo bays would be needed for fuel storage and the slot loss will be around 1 100 TEU. This is assuming that location of the tank can be closer than B/5 to ship side, by using the probabilistic approach.

To reduce the cargo loss following conversion, we propose a reduced range option, where ammonia tanks occupy only a single cargo bay next to the engine room (Figure 9C). In this case (for ammonia conversions only), we assume the auxiliary engines and boiler will be converted as well, to manage boil off gas. This configuration reduces the ammonia range by 65%, down to 7900 nm with a 7000 m^3 tank capacity. This is a significant reduction, but nevertheless still should provide enough range for travelling between Singapore and southern Europe.

The resulting slot loss for this option is around 400 TEU, again assuming the tank can be closer than B/5 to ship side.

When converting from preparation level 0, where normal temp steel grade is used in the cargo hold, that will become tank hold space, we assume that a Type B tank will be used, with only partial secondary barrier needed. If a Type A is to be used, the steel in the future tank hold space should be constructed with low temp steel grade, meeting requirements for secondary barrier.

5.1.2 Bunker station location

In our dual fuel and conversion-ready design proposals (Figure 9A), an open type or semi-enclosed bunker station is arranged at port and starboard side so that parallel body line is sufficiently contacted with bunker barge. In our prepared only conversion designs (Figure 9B and C), the bunker station is located just above the tank, providing the shortest possible bunker line.

5.1.3 Vent mast location

In our dual fuel and conversion-ready designs, we propose locating the vent mast at the front of the vessel, more than 25 m from the accommodation and air inlets. When converting from preparation level 0, we have assumed the vent mast will be in the engine casing area, at an appropriate distance from the funnel and air intakes. When converting from preparation level 0, we have assumed the vent mast can be located in the engine casing area, at an appropriate distance from the funnel and air intakes.

5.2 Preparation levels for ammonia conversion-ready newbuilds

Based on the design proposals we have outlined above, and our assessment of which preparations will have the most impact on reducing complexity during a future conversion, we propose the below preparation levels for ammonia conversion-ready newbuilds.

5.3 Techno-economic analysis of conversions from fuel oil to ammonia

Table 9 shows the CapEx investments for newbuilding and converting each design and preparation level, presented as a percentage of the cost of a standard fuel oil newbuild vessel. The cost of a full dual fuel newbuild is currently uncertain as no typical values exists. We have estimated the cost based on the assumption that that the market has matured and is beyond "first mover" cost levels.

In the graphs (Figure 10), we illustrate the total cost of conversion, including newbuilding CapEx, conversion CapEx, and the cost of lost cargo capacity before and after conversion. Based on this analysis, we provide recommendations for newbuild preparation levels, depending on the expected conversion timeline (Table 10). Our recommended preparation levels are based on the lowest total costs; however, ship owners should carefully consider what is right for them and their own individual circumstances when planning vessels and conversions.

Table 8:3 Preparation level description (fuel oil to ammonia conversions).

	Preparation level 1	Preparation level 2	Preparation level 3
Tank	Hull structure prepared for ammonia tank units in cargo area		
Fuel supply system	System scope must be assessed to allow dimensioning of the fuel preparation room and allow space allocation		
Main Engine	Engine type chosen to allow for later conversion		
Auxiliary engine and boiler	Engine type chosen to allow for later conversion. Boiler furnace sized for ammonia and prepared for new burner.		
General	Trim, stability, and longitudinal strength considered for future conversion		
Bunker station	Space allocated.	Bunker line routing prepared with supports and trunks	Full installation including: Manifold, bunker line, safety system, firefighting, ESD etc.
Fuel preparation room	Space allocated	Room constructed	Power, safety systems and ventilation installed
Ventilation	Space allocated	Arrangement designed and duct supports installed.	Established. Ventilation ducts installed. Sensors and closing systems installed
Piping and electrical installations	Space allocated including possible extension of switchboards	Pipe supports, pipe and cable trunks made. Cable ladders and supports. Spare breaker and busbar installed	Piping, cabling, ventilation ducts installed
Vent mast	Space allocated	Support constructed	Vent mast constructed

Table 9: CapEx investments for newbuild and conversion of 15 000 TEU container vessel from fuel oil to ammonia-fuel oil with varying preparation levels. A 15 000 TEU fuel oil newbuild price is assumed to be 150 Mil. USD.

Full range					
	Preparation level 0 (% of newbuild cost)	Preparation level 1 (% of newbuild cost)	Preparation level 2 (% of newbuild cost)	Preparation level 3 (% of newbuild cost)	Preparation level 4 (% of newbuild cost)
Preparation cost at newbuild	0	1	2	3	16
Conversion cost	24	23	21	19	
Total CapEx	24	24	23	23	
Reduced range					
	Preparation level 0 (% of newbuild cost)	Preparation level 1 (% of newbuild cost)	Preparation level 2 (% of newbuild cost)	Preparation level 3 (% of newbuild cost)	Preparation level 4 (% of newbuild cost)
Preparation cost at newbuild	0	0	2	3	
Conversion cost	19	18	16	14	
Total CapEx.	19	19	18	17	

As the graphs show, for full range conversions on time scales up to eight years, a dual fuel newbuild is the most cost-effective option. This allows optimization of the ammonia and fuel oil tanks to reduce the impact of the large ammonia tank on cargo capacity, with the reduction costs from lost cargo outweighing the increased cost of a dual fuel newbuild for a relatively long period.

For full range conversions after more than eight years, we suggest building a vessel with preparation level 0-1. Since only the installation work can be prepared, and not the expensive tank system, the cost difference between the preparation levels is relatively small. The later conversion will have high impact on cost related to the slot loss after installation, but the increased cargo capacity before conversion outweighs this effect at longer conversion timescales.

A reduced range conversion offers significant savings in total cost, in both CapEx (5-6% of a fuel oil newbuild cost) and cargo loss cost. For reduced range vessels that will be converted to ammonia within six years, we recommend building the vessel at preparation level 3. Due to the significant cost savings on tanks and reduced slot loss, the total cost of a reduced range conversion is less than a full scope ammonia dual fuel newbuild. If a very early conversion is expected, a reduced range dual fuel newbuild could also be considered, as this will likely be less

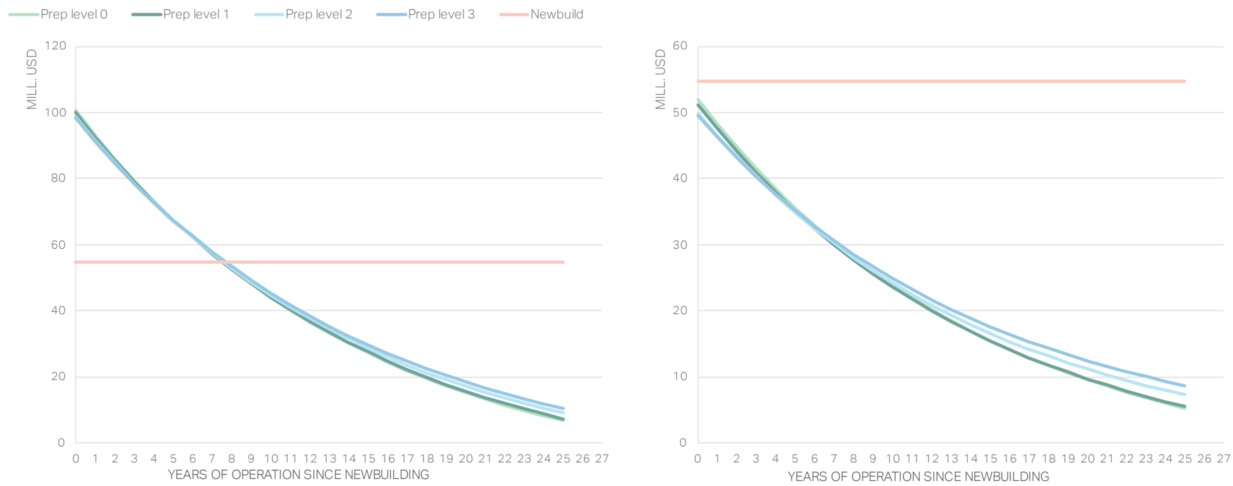


Figure 10: Present value of total conversion cost of a 15 000 TEU container vessel, fuel oil to ammonia, full range (left) and reduced range (right).

Table 10:4 Recommended preparation levels for ammonia conversion-ready vessels based on range and conversion timelines. PV= present value.

Full range		
Years of operation since Newbuild	0-8 years	8-25 years
Lowest PV cost option	Dual fuel newbuild	Preparation level 0 or 1
Reduced range		
Years of operation since Newbuild	0-6 years	6-25 years
Lowest PV cost option	Preparation level 3	Preparation level 1

expensive than a full scope dual fuel newbuild. The ammonia range is, however, critical to a newbuild, where high trading flexibility is normally required. Furthermore, a full range ammonia vessel may be required when availability is limited, and frequent bunkering is not feasible. Adding tanks when required could be a feasible option for longer range and increased flexibility, however, this approach will require its own techno-economic analysis.

For reduced range vessels that will be converted after more than six years we recommend building the vessel at preparation level 1, reducing initial preparation costs and cargo losses. The total cost difference between preparation level 0 and 1 is minimal and as a result preparation level 1 is recommended, allowing space is allocated for future installations.

The value of the cargo loss can vary, impacting total costs. We conducted a sensitivity analysis to investigate the effects of varying slot loss values on the outcomes of our analysis. We found that while changing the slot loss values in the model impacts the total cost, it does not change our cost observations or recommendations.

Off-hire costs are not included in our model but could also impact conversion costs. Off hire cost for a container vessel is very dependent on the market situation. In a sensitivity analysis, we found that for each one mil USD in off hire cost that is added to cost of conversion, the break-even date between a dual fuel newbuild and a conversion option is extended by just 0.1 year. As a result, we concluded that the impacts of off-hire costs are minimal.

5.4 GHG assessment (fuel oil to ammonia conversions)

Figure 11 illustrates the total lifetime CO_2 emissions for vessels converted after 5 or 10 years compared with a reference vessel operating on fuel oil for the lifetime of the vessel. This is based on a yearly total fuel consumption of 29 200 mt fuel oil and a 25-year lifetime. Emissions after

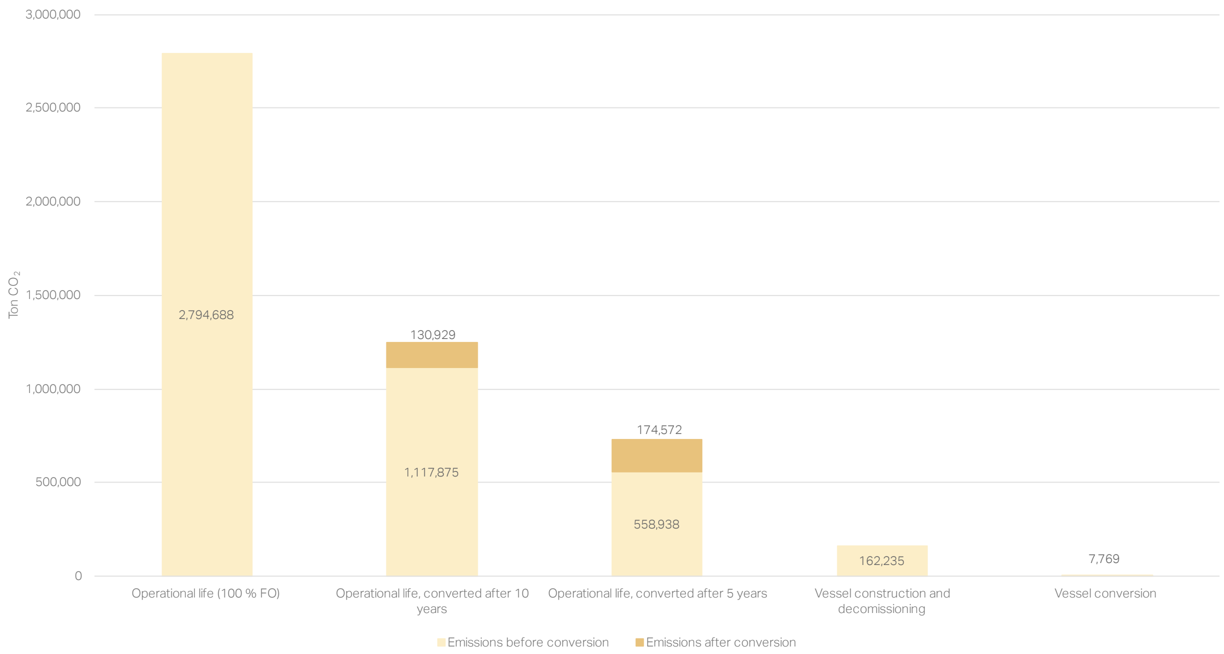


Figure 11: CO_2 emissions, 15 000 TEU container vessel, fuel oil to ammonia conversions, full range.

conversion are from the pilot fuel oil (8%) needed for main and auxiliary engines. In case a CO_2 neutral oil is used as pilot oil, the emissions after conversion can be considered zero. CO_2 emissions related to building and scraping a vessel, as well as conversion of the vessel are illustrated for comparison, showing that the emissions for the conversion are minimal compared to operational emission.

6 LNG to ammonia conversions

In this section, we provide proposed designs for converting a 15 000 TEU container vessel from LNG-fuel oil to ammonia-fuel oil. The conversion from LNG to ammonia is somewhat different from converting from fuel oil as many of the gas fuel handling systems required for ammonia are also required for LNG. As a result, we only describe one new build preparation level (preparation level 3) for both full and reduced range. After conversion from LNG to ammonia the vessel will no longer be able to operate on LNG and will be an ammonia-fuel oil dual fuel vessel. Our proposed designs aim to minimize cargo loss and conversion complexity, while adhering to the regulations and other technical requirements outlines in Section 3.

We also provide a techno-economic analysis of the total costs of conversion depending on the desired range. Like the conversion case from fuel oil to ammonia, we compare the total cost for converting a prepared LNG fueled vessel to ammonia with an ammonia-fuel oil new build. As the reference fuel for these options is not the same, (fuel oil vs LNG), an assumed fuel oil-LNG saving of 140USD/ton fuel oil equivalent, is included in the total cost calculations. (This value is based on traditional market conditions).

Based on the results of this analysis, we recommend either an ammonia-fuel oil dual fuel vessel at newbuilding or an LNG-fuel oil vessel prepared for conversion to ammonia later, depending on when conversion is expected.

6.1 Proposed designs for LNG-ammonia conversion-ready vessels

6.1.1 Tank arrangement

In a 15 000 TEU LNG-fuel oil container vessel, we expect that the fuel tanks will be located partly under the accommodation, to reduce cargo loss. This tank cannot practically be removed, and therefore, must be prepared for ammonia. We have assumed that a fully ammonia-prepared membrane tank will be used, however this tank solution is not fully developed yet. Stainless B-type tanks could also provide a solution, but we have not included them in our designs as we are not aware of any currently available ammonia-ready LNG B-type tank designs. The LNG/ammonia tank in our proposed full range design is 20 000m^3, resulting in a slot loss of around 540 TEU.

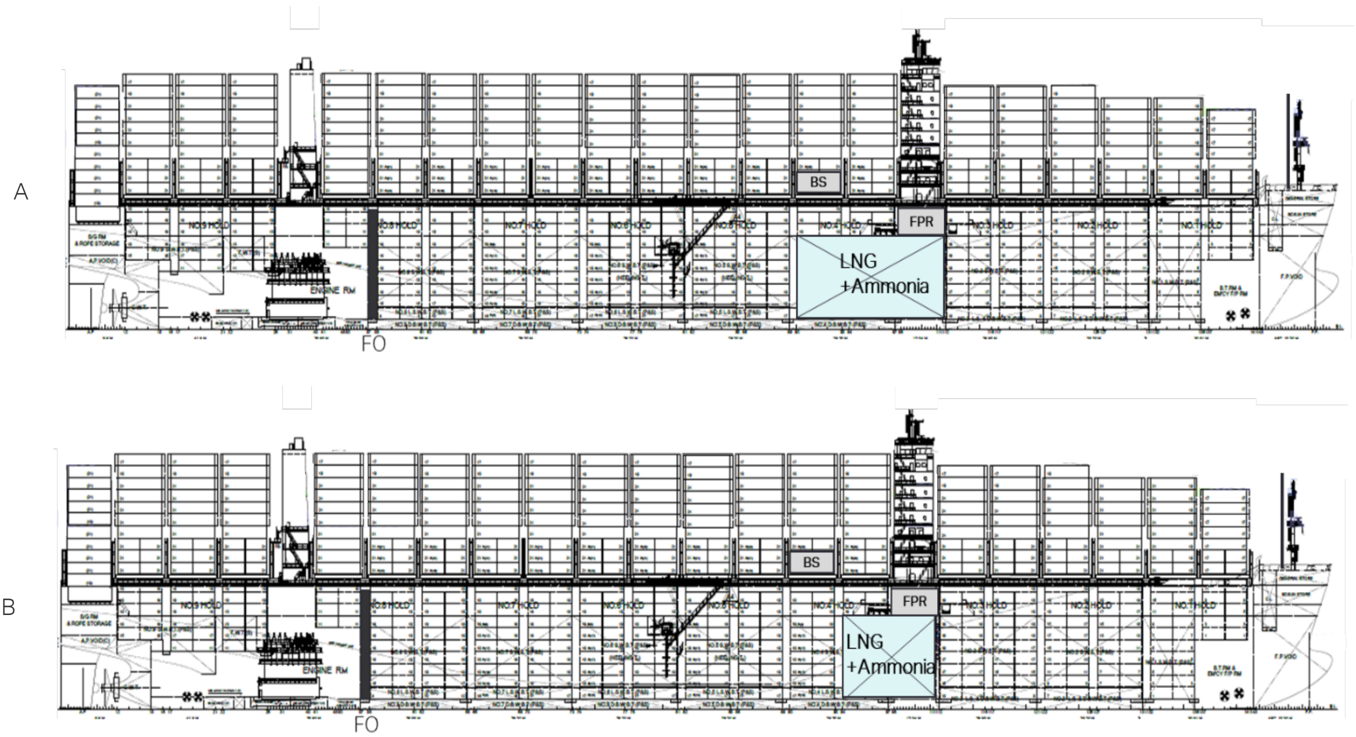


Figure 12: 4Designs for a 15 000 TEU container vessel for conversion from LNG-fuel oil to ammonia-fuel oil. (A) Full range (20 000 m^3) LNG/ammonia-fuel oil vessel. (B) Reduced range (12 000 m^3) LNG/ammonia-fuel oil vessel. FPR= fuel preparation room, FO=fuel oil, BS=bunker station.

We suggest locating the fuel oil tanks between the cargo holds (in our designs they are located just in front of the engine room) with the number of tanks and dimensions determined by the required fuel oil range post conversion.

We have also proposed a design for a reduced range vessel with a tank capacity corresponding to full range for LNG (12 000m^3), a reduction of 60% compared to full range for ammonia.

6.1.2 Bunker station and vent mast location

In both designs an open type or semi-enclosed bunker station is arranged at port and starboard side so that parallel body line is sufficiently contacted with bunker barge. We propose locating the vent mast at the front of the vessel, a safe distance of over 25 m from the accommodation and air inlets.

6.2 Preparation level for LNG to ammonia conversion

For an LNG fueled container vessel, although the existing tanks will need to be prepared for ammonia, many other structures, and systems necessary for ammonia are already in place: double walled piping is already routed, a fuel preparation room is established, and vent mast is already constructed. As a result, although the existing structures must still be prepared for ammonia, the vessel is already at preparation level 3 and we have not considered any lower preparation levels.

In cases where the existing LNG tanks cannot be prepared for ammonia, we do not expect that it will be practically possible to replace the LNG tanks located under the accommodation, and as a result, conversion to ammonia would not be feasible for this type of vessel.

6.3 Techno-economic analysis of LNG-ammonia conversions

We calculated the CapEx investments for newbuilding and converting each design presented as a percentage of the cost of an LNG-fuel oil dual fuel newbuild, see Table 12. When preparing the vessel for full range on ammonia, a larger, ammonia-ready tank is required. We have included these costs in the preparation costs at newbuild.

Table 12: 5LNG - Ammonia conversion CapEx from preparation level 3 (CapEx is % of LNG-fuel oil dual fuel newbuild). A 15 000 TEU LNG newbuild is assumed to be 174 Mil. USD.

	Full range cost (% of LNG newbuild cost)	Reduced range cost (% of LNG Newbuild cost)
Preparation cost at newbuild	7	2
Conversion cost	8	8
Total CapEx	15	10

Table 11:6 Preparation level description (LNG to ammonia conversions).

*An LNG fueled vessel is assumed to use the auxiliary engines and boiler for boil off gas management. The possibilities for converting an LNG dual fuel auxiliary engine and LNG boiler to ammonia is not known at this point, but we assume it will be possible, with same cost level at conversion from fuel oil to ammonia.

	Preparation level 3
Tank	Tank is built and designed for cryogenic temperature of LNG and the density and material requirements of ammonia.
Fuel supply system	LNG system is designed and arranged for easy replacement with ammonia equipment
Main Engine	Engine type chosen to allow for later conversion
Auxiliary engine and boiler*	Engine type chosen to allow for later conversion
Bunker station	Bunker station designed and installed according to both LNG and ammonia requirements, including material. This includes sizing of manifold and bunker line to accommodate ammonia volumes.
Fuel preparation room	The LNG fuel preparation room is dimensioned to accommodate ammonia supply system, circulation tank and reliquification equipment required for ammonia
Ventilation	Ventilation system dimensioned for ammonia emergency ventilation
Piping & Electrical installations	Bunker line dimensioned for expected ammonia bunkering volumes, and stainless-steel piping used. Switch boards and cabling dimensioned for highest consumer
Vent mast	Vent mast dimensioned and located according to requirements for ammonia.

Table 13:7 LNG - Ammonia conversion CapEx. CapEx in % of standard fuel oil newbuild for comparison with ammonia-fuel oil conversions. A 15 000 TEU fuel oil newbuild price is assumed to be 150 Mil. USD.

	Full range cost (% of FO newbuild cost)	Reduced range cost (% of FO new build cost)
LNG-ammonia preparation level 3 newbuild + conversion	33	28
Ammonia-fuel oil newbuild	16	-

As the result of this conversion is an ammonia-fuel oil dual fuel vessel, we compared the costs of LNG-ammonia conversion to a full range ammonia-fuel oil dual fuel new build, see Table 13.

In the graphs below (Figure 13), we illustrate the total cost of an ammonia-ready LNG vessel compared with an ammonia-fuel oil newbuild, including newbuilding CapEx, conversion CapEx, and lost cargo capacity before and after conversion. As operating on LNG prior to conversion provides savings in fuel costs compared with operating on fuel oil, we have included these savings in our total cost assessment. Fuel cost savings are assumed to be 140 USD/ ton fuel oil equivalent (based on Center NavigaTE fuel costs).

Based on this analysis, we provide recommendations for building either an ammonia-ready LNG vessel or an ammonia-fuel oil newbuild, depending on the expected conversion timeline (Table 14). Our recommended preparation levels are based on the lowest total costs;

Table 148: Recommendations for building conversion-ready LNG vessels or ammonia-fuel oil newbuilds depending on desired range and conversion timelines based on analysis of a 15 000 TEU container vessel. PV= present value.

Full range		
Years of operation since Newbuild	0-8 years	8-25 years
Lowest PV cost option	Ammonia -fuel oil newbuild	Preparation level 3
Reduced range		
Years of operation since Newbuild	0-1 years	1-25 years
Lowest PV cost option	Ammonia -fuel oil newbuild	Preparation level 3

however, ship owners should carefully consider what is right for them and their own individual circumstances when planning vessels and conversions.

The cost of preparing an LNG fueled vessel for full range ammonia is high as it includes LNG configuration costs, a larger tank and specific preparation for ammonia. As a result, an LNG-ammonia conversion is a relatively expensive option, and it takes eight years for the cheaper LNG operation to make up for these costs (assuming a fuel oil-LNG saving of 140USD/ton fuel oil equivalent). For conversion to remain a relevant option up to 10 years after newbuilding, the cost spread must be at least 107 USD/ton fuel oil equivalent.

For reduced range conversions, the reduced tank costs and lower cargo losses make a conversion ready LNG vessel a much less expensive option, with a lower total cost than a full range ammonia-fuel oil newbuild, even if converted after only a year of operation.

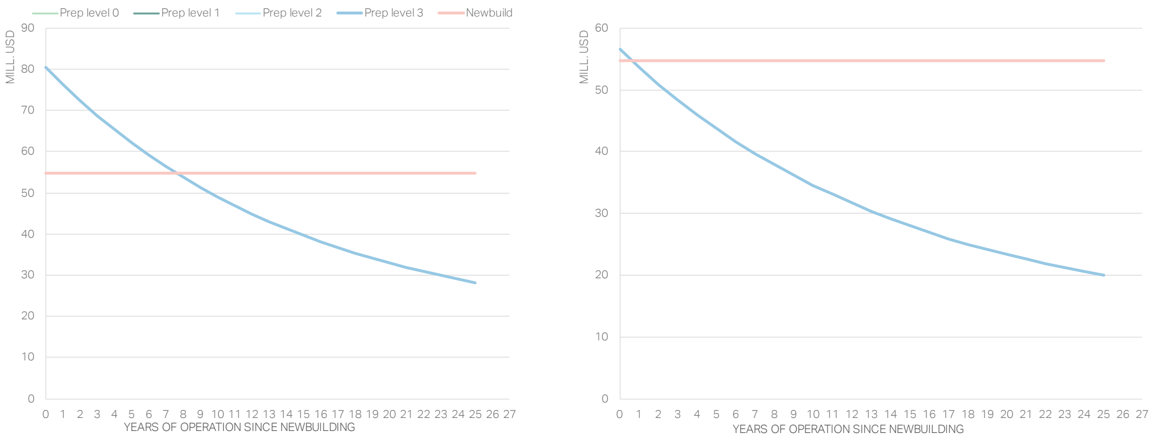


Figure 13: Present value of total conversion cost of a 15 000 TEU container vessel from LNG to ammonia compared with an ammonia-fuel oil dual fuel newbuild, full range (left) and reduced range (right).

6.4 GHG assessment (LNG to ammonia conversions)

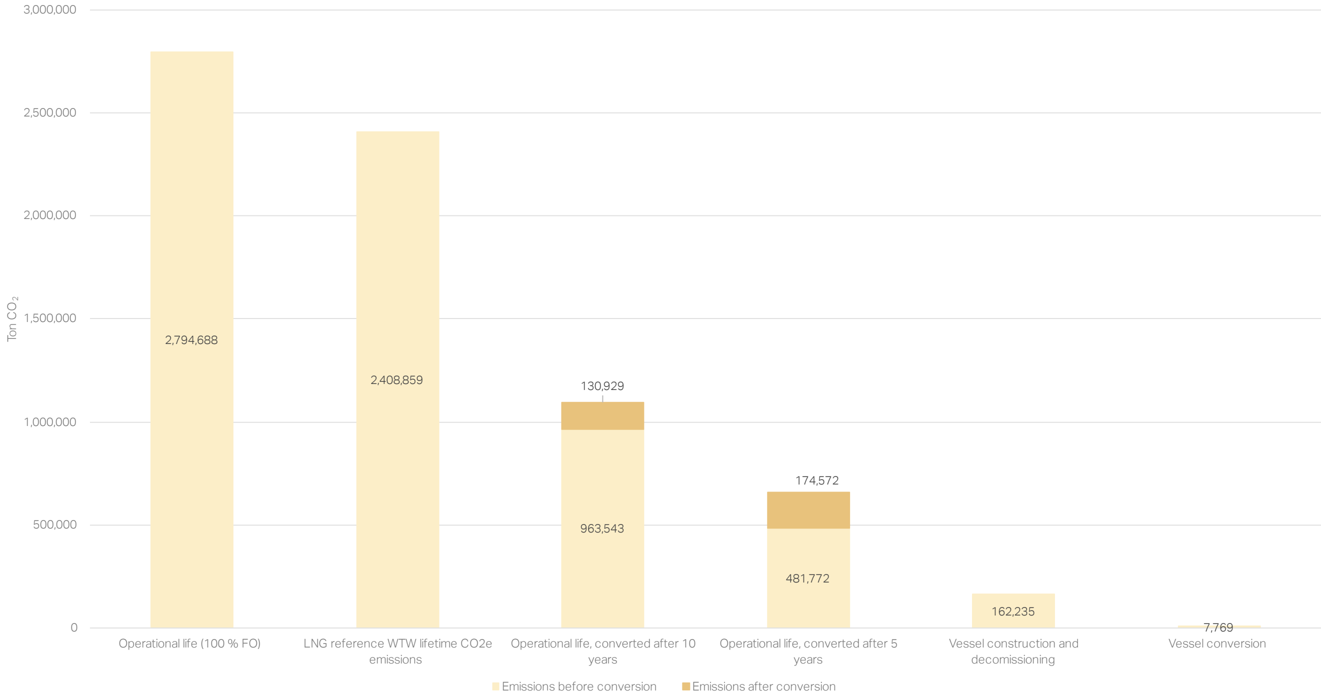


Figure 14:5 CO_2 emissions, 15 000 TEU container vessel, LNG to ammonia conversion, full range and scope.

Figure 14 illustrates the total lifetime CO_2 emissions for vessels converted after five or ten years compared with a reference vessel operating on fuel oil for the lifetime of the vessel. This is based on a yearly total fuel consumption of 29 200 mt fuel oil and a 25-year lifetime. Emissions after conversion are from the pilot fuel oil (8%) needed for main and auxiliary engines. In case a CO_2 neutral oil is used as pilot oil, the emissions after conversion would be zero.

CO_2 emissions related to building and scraping a vessel, as well as conversion of the vessel are illustrated for comparison, showing that the emissions for the conversion are minimal compared to operational emission. The emission related to building a new vessel, is equal to around 1.5 years emission from operating on fuel oil or 1.7 years of operation on LNG.

7 Conclusions

The work we have presented here shows that although preparing for the transition to alternative fuels requires additional upfront investment, preparation can pay off in the long term with intelligent ship design and careful planning of conversion timelines

Building dual fuel and conversion-ready new builds typically increases newbuild CapEx by 1-16% of the cost for a standard fuel oil newbuild, depending on the planned alternative fuel, desired range, and preparation level. Total CapEx for newbuilding and conversions range from 10-33% of the cost of a standard fuel oil newbuild (see Table 15).

The increased tank volumes required for methanol and ammonia mean that costs associated with lost cargo have a big impact on the total lifetime costs. In the twin island vessel design used here, lost cargo space can be reduced by placing tanks under the accommodation, but this must be done during the newbuild phase, which increases newbuild costs and the risks associated with committing to a particular future fuel. When tank preparation is not possible and additional alternative fuel tanks must be added in cargo areas later, this has a large impact on costs from cargo losses.

We have analyzed the total costs of newbuilding, conversion and cargo losses for vessels with different preparation levels for each fuel and provided recommendations for newbuild readiness levels, depending on the desired future fuel, conversion timelines,

Table 15: CapEx and cost summary for conversion of a 15 000 TEU container vessel.

Container vessel	Methanol or ammonia dual fuel newbuild cost	Full range conversion cost (Preparation level 3-0)	Reduced range conversion cost (Preparation level 3-0)
Fuel oil to methanol (% of fuel oil newbuild cost)	11	14-16	11– 12
Fuel oil to ammonia (% of fuel oil newbuild cost)	16	23 – 24	17 – 19
LNG to ammonia (% of LNG newbuild cost)		15	10
LNG to ammonia Total add on cost. (% of fuel oil newbuild cost)		33	28

and range (see Figure 15,16). The costs of conversion mean that for short conversion timelines (3-8 years), dual fuel vessels make economic sense. In most cases where conversion is expected in a timeline of 8-10 years, and full range for the alternative fuel is required, some degree of preparation reduces the total costs.

Converting unprepared vessels only makes economic sense on longer timelines or where reduced range options reduce cargo loses. However, the different preparation levels (1-3) we analyzed only had a small impact on newbuild and total costs and very little impact on the total lifetime cost. However, in general the earlier you expect to convert, the more you should prepare. The desired range after conversion, on the other hand, has a much larger influence on conversion CapEx, and therefore the total lifetime cost. Reduced range vessels may offer cost effective options for conversion, where feasible.

When converting from LNG to ammonia, some of the required installations for ammonia are already installed, and as a result the conversion costs are lower than converting from fuel oil. When compared with an ammonia-fuel oil dual fuel newbuild, the total CapEx add-on including LNG option and the conversion cost, is around 30% of a fuel oil newbuild price. Our study shows that the additional cost for the LNG option is recovered over the period before conversion to ammonia because of the assumed lower cost of LNG as fuel, however the fuel price of LNG compared with fuel oil has a big impact on this calculation. If an LNG vessel's fuel tank is not prepared at newbuild phase, then conversion to ammonia is not feasible for this type of vessel.

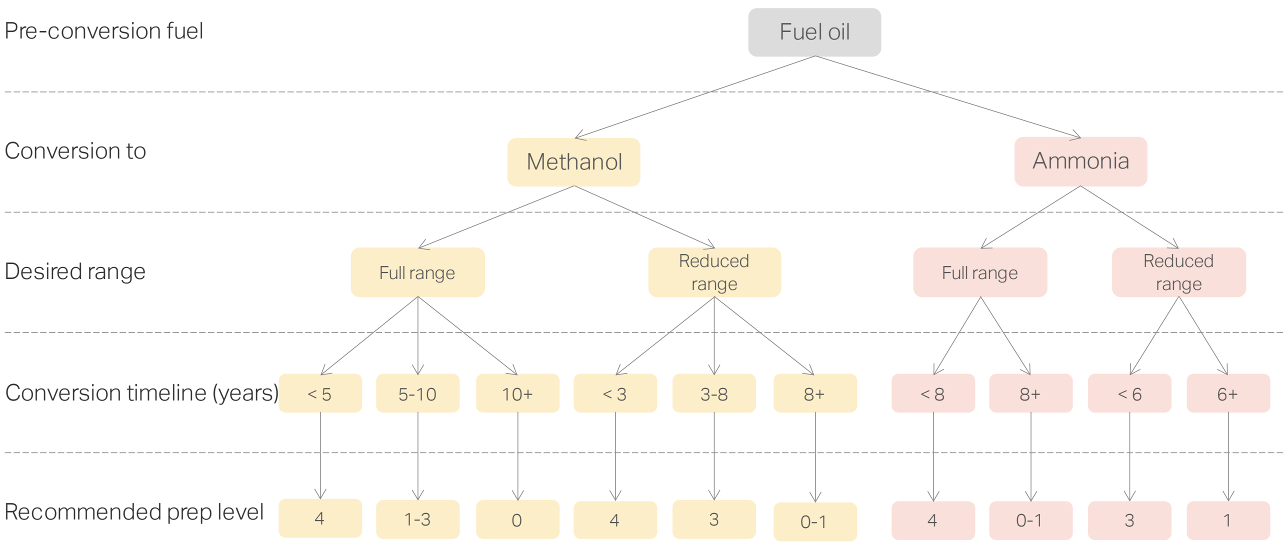


Figure 15: Recommended preparation levels for conversions from fuel oil to methanol or ammonia based on conversion timelines and desired range.

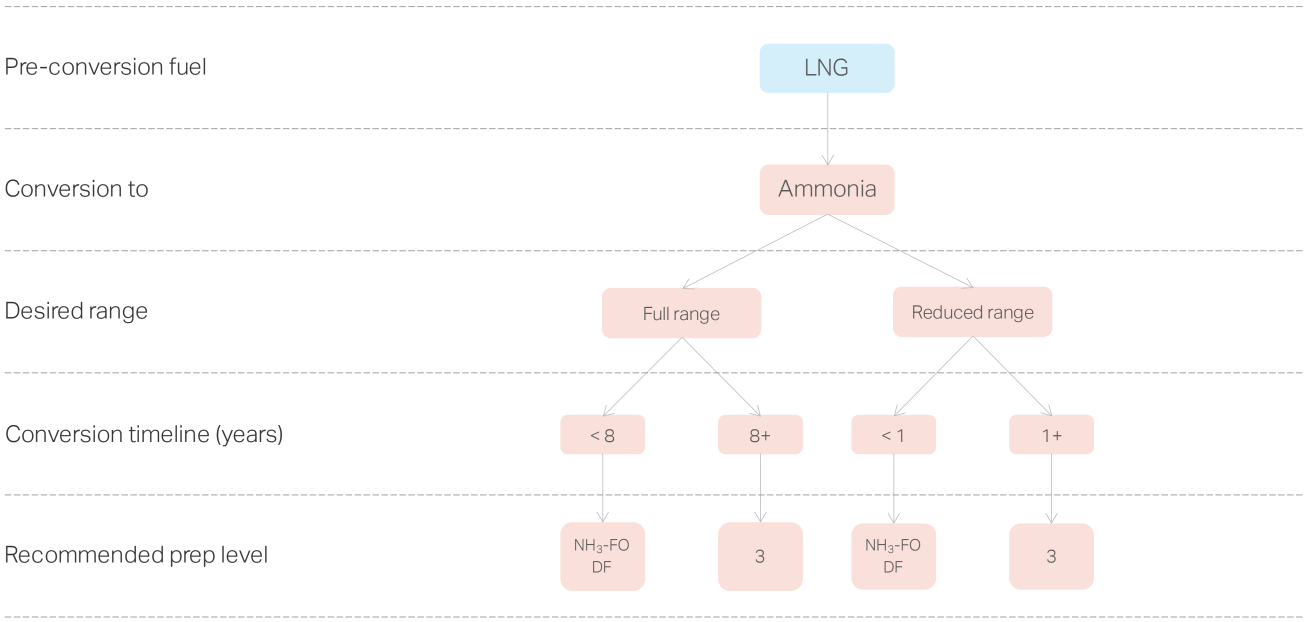


Figure 16: Recommendations for conversions from LNG to ammonia based on conversion timelines and desired range. DF=dual fuel.

Our emissions analyses showed that CO_2 emissions from the conversion is minimal, at around 0.3% of the lifetime emissions of a fuel oil vessel. If the vessel is replaced with a newbuild, instead of converted, the emissions related to building a new vessel, is equal to around 1.5 years emissions from operating on fuel oil or 1.7 years of operation on LNG. This shows that conversion is also a valid option from an emission reduction perspective.

8 The project team

This report was prepared by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) with assistance from our partners.

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