Preparing Tanker Vessels for Conversion to Green Fuels

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

Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

Executive summary

Transitioning the world fleet to climate-friendly alternative fuels is essential for decarbonization of the shipping industry. However, vessels being built or ordered today will likely be operating for decades to come, and many alternative fuels are not yet available at scale.

Therefore, shipowners face a challenge in choosing which alternative fuel and technologies they should build their decarbonization strategies around, as well as how to most effectively time their investments in these solutions. For example, is it better to build a vessel that is ready to operate immediately on alternative fuels such as methanol or ammonia, or a vessel that can be converted to operation on these fuels at a later date - and, if the latter, how much should be invested in preparation for the alternative fuel at the newbuilding stage versus in later retrofitting?

To help address these challenges, the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) has analyzed the technical, economic, and environmental impacts of preparing vessels for conversion to alternative fuels. Using insights from project partners, the project aimed to understand the technical requirements and cost of converting from fuel oil to methanol or ammonia and from liquefied natural gas (LNG) to ammonia. This report outlines the project results related to converting tanker vessels to methanol or ammonia fuels. It follows an earlier report from the same project focused on container vessels.

Vessel design and operational considerations

The report considered reference designs for two types of tanker vessels: LR2 and VLCC. These vessel types are two of the largest in the tanker segment, often travel long routes, and have a high fuel consumption — therefore, they can provide a good illustration of the economic and environmental impacts of different choices relating to vessel conversion. For each vessel design, we defined five levels of preparation for alternative fuels, ranging from no preparation (Level 0) to a dual-fuel newbuild ready to operate on methanol or ammonia (Level 4).

Alternative fuels are less energy-dense and so require more storage space than fossil fuels for the same distance traveled. Therefore, the interaction between fuel storage capacity, cargo capacity, and vessel range was a key consideration for this study. For this reason, we included options for transitioning the vessel to a reduced, but still commercially relevant, range after conversion.

The storage requirements for alternative fuels for the LR2 design can be met using tanks located on the deck, without affecting the vessel's range. This leads to a minimal impact on the LR2's standard parcel size and cargo capacity. However, additional tanks and fuel volume will decrease the vessel's deadweight tonnage (DWT).

For the VLCC design, maintaining the same range after conversion to methanol or ammonia would require installing fuel tanks in the cargo space, leading to a loss of cargo capacity. We generally consider that a full-range VLCC operating on ammonia would not be commercially viable. However, operating the VLCC with a reduced range after conversion to either methanol or ammonia would allow all fuel tanks to be located on the deck, preserving the cargo space. The reduced range option for the VLCC is based on a trade route from the Persian Gulf to the Far East, which is relevant for this segment.

Techno-economic analysis

For the LR2 design, our model indicates that the total add-on cost of newbuilding and conversion to operation on methanol or ammonia, depending on preparation level and range, is:

14-27%
of the cost of a standard fuel oil newbuild for fuel oil-methanol conversions

25-42%
of the cost of a standard fuel oil newbuild for fuel oil-ammonia conversions

47-62%
of the cost of a standard fuel oil newbuild (or 21-34% of the cost of an LNG newbuild) for LNG-ammonia conversions

Considering the different preparation levels in our study, we found that a dual-fuel newbuild vessel makes the most economic sense if operation on the alternative fuel is expected in 5-7.5 years when converting from fuel oil, or 10.5-12 years if converting from LNG. If building a vessel for later conversion, the best preparation level depends on conversion timeline. Choice of preparation level can impact capital expenditure (CapEx) at the newbuilding stage by 1-3% of the cost of a fuel oil newbuild or around 2-4% of the cost of an LNG newbuild.

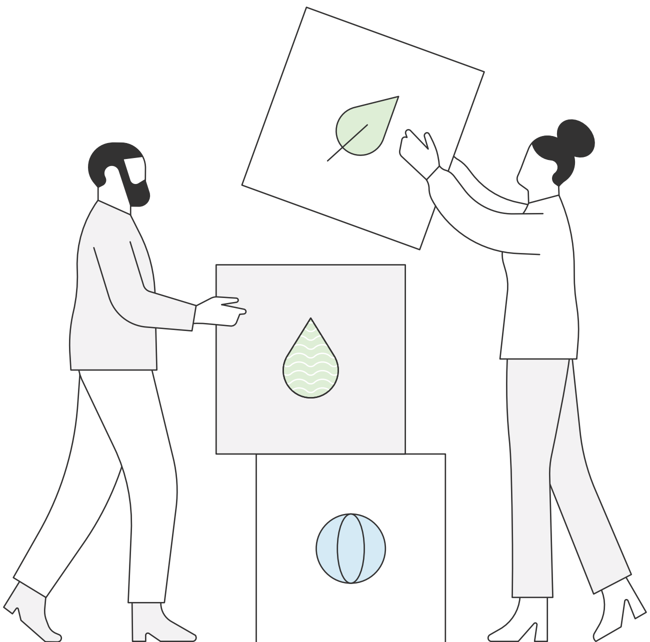
For the VLCC design, we generally considered that maintaining the vessel's full range after conversion is not economically viable. If we consider only the options with reduced range after conversion, the estimated total add-on cost of newbuilding and conversion, depending on preparation level, is:

17-29%
of the cost of a standard fuel oil newbuild for fuel oil-methanol conversions

31-45%
of the cost of a standard fuel oil newbuild for fuel oil-ammonia conversions

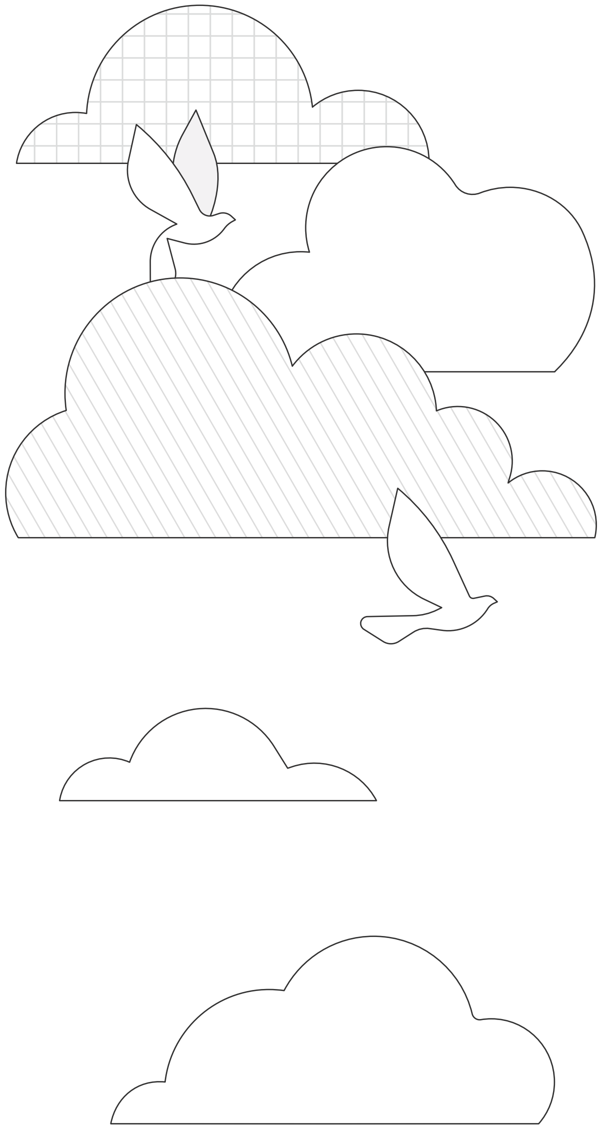
50-63%
of the cost of a standard fuel oil newbuild (or 17-28% of the cost of an LNG newbuild) for LNG-ammonia conversions

If we continue to assume a reduced range following conversion, a dual-fuel newbuild is the most economical option if operation on alternative fuels is expected within 4-6 years. For conversions, the choice of preparation level again depends on timeline, and it can impact newbuild CapEx by 1-6% of the cost of a fuel oil newbuild or 5-7% of the cost of an LNG newbuild.



Impact of conversion on greenhouse gas emissions

Our analysis indicates that conversion of tanker vessels to operation on alternative fuels after five or even ten years of operation on fossil fuels creates a large reduction in lifetime operational greenhouse gas (GHG) emissions. Furthermore, the CO_2 emissions resulting from the conversion itself are minimal — equivalent to around 0.5% of the vessel's lifetime operational emissions using fossil fuels.



Key takeaways

Converting tankers to green fuels can be technically and economically feasible when carefully considered in the context of fleet transition planning and asset age profiles. The industry has the right technology and engineering knowledge in place to achieve such conversions. When it comes to the economic impact, the differences in CapEx vary depending on the desired green fuel and vessel range chosen. In general, the most cost-effective option is tanker conversion from fuel oil to methanol, followed by conversion to ammonia.

It is important to highlight that conversion to alternative fuels impacts a vessel's operating envelope, due to the energy density of the alternative fuels and their corresponding fuel tank size requirements. To keep the same operational range as on fossil fuels, shipowners must consider either adding tanks on deck (with a resulting impact on DWT) or giving over part of the cargo capacity to fuel tanks. As part of this project, we have focused on options that reduce the vessel's operating range but preserve its cargo capacity. Based on industry knowledge, we believe that such solutions have commercial applicability.

Lastly, our analysis here shows that even conversions after ten years of operation on fossil fuels can still yield considerable environmental impact. However, one must also consider the financial viability of making such a CapEx investment at this point in the vessel's lifetime.

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01 Introduction

This project report outlines our technical, economic, and environmental analysis of preparing tanker vessels for conversion to alternative fuels. Read on to learn about 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.[3, 4]

As the path to zero continues to develop, if you are a shipowner, you will probably face an increasing set of dilemmas: Should you invest now in dual-fuel newbuilds that can run on both traditional and alternative fuels? Are conversion-ready vessels with lower upfront costs a better option? How ready should a conversion-ready vessel be? Or should you 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 many technical and regulatory considerations. For example, retrofitting requires modification of existing structures and installations that are difficult to access in a finished vessel.

Dual-fuel newbuilds are an attractive option to avoid the higher cost and complexity of potential later conversions. However, they require more upfront investment, which 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. Furthermore, if full or long range is needed, the alternative fuel tanks may take up cargo space 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, with space allocated for future installations or key steel construction elements included. This reduces both the initial investment and the impact on cargo space, but introduces conversion costs later. However, it is still challenging to know whether a conversion-ready vessel 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. During the project, we analyzed the technical, economic, and environmental impacts of preparing container vessels and tankers for conversion to alternative fuels. We published the results of our analyses related to container vessels in September 2022.[5] This report focuses on preparing tanker vessels for conversion.

1 Ready, set, decarbonize! Are shipowners committed to a net zero future?, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022.
2 Position Paper: Fuel Option Scenarios. Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021.
3 EU Commission President names landmark methanol vessel "Laura Mærsk" (press release), Maersk, 14 September 2023.
4 The world's first clean ammonia-powered container ship (press release), Yara, 30 November 2023.
5 Preparing Container Vessels for Conversion to Green Fuels, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022.

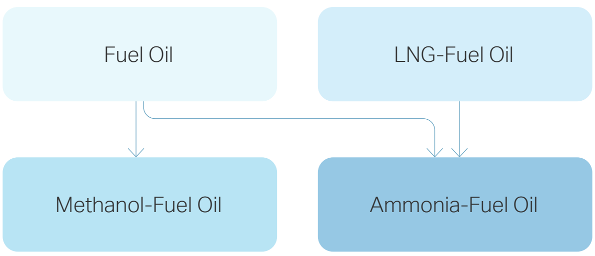
02 About this project

This report is part of the Green Fuels Optionality project, a collaboration between the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) and our partner organizations: the American Bureau of Shipping (ABS), A.P. Moller-Maersk (Maersk), MAN Energy Solutions, Mitsui, Mitsubishi Heavy Industries (MHI), NYK Line, TotalEnergies, and Seaspan. The objectives of this project are to assess the technical, economic, and environmental consequences of converting ships from fossil-based fuels to green fuel solutions; and to recommend preparation levels for conversion-ready newbuilds that facilitate subsequent fuel transition and reduce future costs.

In this report, we focus on the technical and regulatory requirements for dual-fuel tanker vessels. Based on the knowledge and experience of project partners, we proposed reference designs for two tanker vessel segments: 1) a long-range 2 (LR2) vessel with a deadweight tonnage (DWT) of 115,000 and overall length (LOA) of 250 meters, and 2) a very large crude oil carrier (VLCC) vessel with a DWT of 300,900 and LOA of 340 meters. These vessels represent two of the largest tanker segments and have a relatively high fuel consumption, making them illustrative examples for this project.

Fuel conversion options considered in this report are summarized in Figure 1. The report covers vessel conversions from conventional fuel oil to methanol and to ammonia, and from liquefied natural gas (LNG) to ammonia. In all cases, the converted vessels are assumed to be dual-fuel (i.e., the engines can run on both fuel oil and another fuel). Although conversion from LNG to methanol is also a possibility, this option is not included in the report, as market trends indicate greater interest in LNG to ammonia conversions. Similarly, we have not considered conversion of liquefied petroleum gas (LPG)-fueled vessels, as LPG is not commonly used as a fuel in the tanker segment. Conversion from fuel oil to LNG (or other methane-based fuels) has been widely studied and so is also excluded from the report. We also have not considered transitions from fossil fuels to bio-diesel or from fossil LNG to bio- or e-methane, as these fuel changes can be implemented with minor or no modifications to the vessel's fuel system. Conversions to hydrogen fuel are also excluded, as hydrogen is not yet deemed a viable fuel solution for long-range oceangoing vessels.[6]

Figure 1: Maritime fuel conversion pathways analyzed in this project.



LNG = liquefied natural gas.

Newbuild vessels can be constructed with different levels of preparation for non-fossil fuels. The chosen preparation level affects the cost and time needed for eventual conversion to a new fuel type. For this report, we considered five different preparation levels

6 Maritime Decarbonization Strategy 2022: A decade of change, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022.

ranging from no preparation (Level 0) to fully dual-fuel vessels (Level 4). For each vessel design in the study, we conducted a techno-economic assessment to investigate both the financial and environmental impacts of conversion. We considered the total costs for each vessel, including expenses associated with initial construction, conversion, and lost cargo capacity. We analyzed these costs in relation to different conversion timelines, enabling us to identify optimal recommendations for vessel preparation level and time to conversion. We also assessed the environmental impacts of fuel conversion based on vessels' estimated total lifetime greenhouse gas (GHG) emissions.

2.1 Technical considerations for dual-fuel vessels and conversions

The properties of alternative fuels such as methanol and ammonia are significantly different from those of traditional fuel oil. As a result, many technical details must be carefully considered when planning a methanol or ammonia dual-fuel newbuild vessel or a conversion to these alternative fuels. For example, the lower energy density of methanol and ammonia means that conversions require additional fuel storage space. Furthermore, additional safety considerations and regulatory restrictions associated with handling toxic gases and low-flashpoint fuels must be considered when using ammonia or methanol.

In our previous publication, 'Preparing Container Vessels for Conversion to Green Fuels', we summarized the key technical aspects that must be carefully considered when planning a dual-fuel vessel or 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 (FPR), fuel supply systems, fuel piping, engine conversion, after-treatment and certification, ventilation and venting systems, fire prevention and detection, toxicity, and hull design. For more details, see the Preparing Container Vessels for Conversion to Green Fuels report.

Of note, our design considerations for the methanol storage system on container vessels were based on structural tanks, whereas methanol fuel can be stored on tankers in a combination of structural and International Maritime Organization (IMO) Type C tanks. In our previous report on Preparing Container Vessels for Conversion to Green Fuels, we assumed that the methanol tanks would be used to store fuel oil until methanol fuel was implemented, to save space for both fuel oil and methanol tanks. However, this assumption is not relevant for the tanker vessel designs, as the fuel oil tanks for these vessels generally do not impact the available cargo volume.

2.2 Range of dual-fuel vessel designs

For comparative purposes, we initially considered vessel designs that would maintain their original range following fuel conversion. However, as both ammonia and methanol have a lower volumetric energy density than conventional fuel oils, vessels using these alternative fuels will require considerably more fuel to maintain the same range, as summarized in Table 1. For example, an LR2 tanker can travel 19,000 nautical miles (NM) with a total fuel tank volume of 2,480 cubic meters (m^3) when using fuel oil, but the same distance requires a fuel tank volume of approximately 7,100 m^3 when using ammonia (Table 1).

Table 1: Full-range fuel tank capacities for different tanker vessels and fuel types.

Vessel type	Range (NM)	Fuel oil	Methanol	Ammonia	LNG
LR2	19,000	2,480 m^3	5,400 m^3	7,100 m^3	4,400 m^3
VLCC	25,000	6,400 m^3	15,900 m^3	19,800 m^3	12,000 m^3

LNG = liquefied natural gas.

This increased fuel requirement will reduce the cargo carrying capacity, which is undesirable from a commercial perspective. Our reference designs are based on existing tanker models, with large fuel tanks located on deck above the cargo hold. The addition of larger fuel tanks and the weight of the required volume of ammonia or methanol will decrease the vessel's DWT, meaning that less cargo can be carried.

Therefore, we have also investigated designs for vessels with a reduced range following fuel conversion, which would allow the vessel to maintain a larger cargo hold capacity. Specifically, the reduced-range option for the LR2 vessel was based on the range of existing LNG-fueled LR2 tanker designs with an estimated range of 15,500 NM and an associated LNG capacity of 3,500 m^3. The reduced-range VLCC was based on a range of 14,000 NM. For reference, this range is equivalent to a route from the Persian Gulf to the Far East (PG-FE). The tank capacities selected for reduced range designs are given in Table 2. In these cases, the range when using fuel oil remains the same as for the full-range options. We also note that the ranges described here are based on design speed, and longer ranges can likely be achieved by reducing the vessel's speed.

The LNG capacity for the reduced-range VLCC is the same as the ammonia capacity, as the tanks in this case study are assumed to be ready for ammonia, and no additional tank installations are required when converting. The LNG capacity is around 24,000 NM, close to full range.

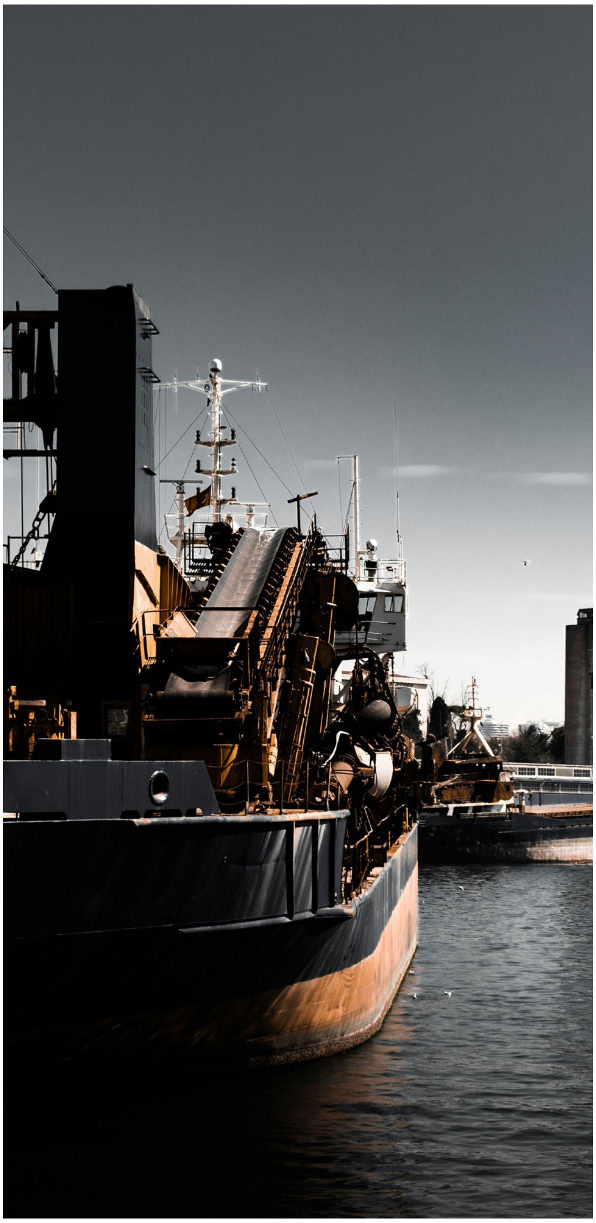


Table 2: Selected reduced-range fuel tank capacities for different vessels and fuel types.

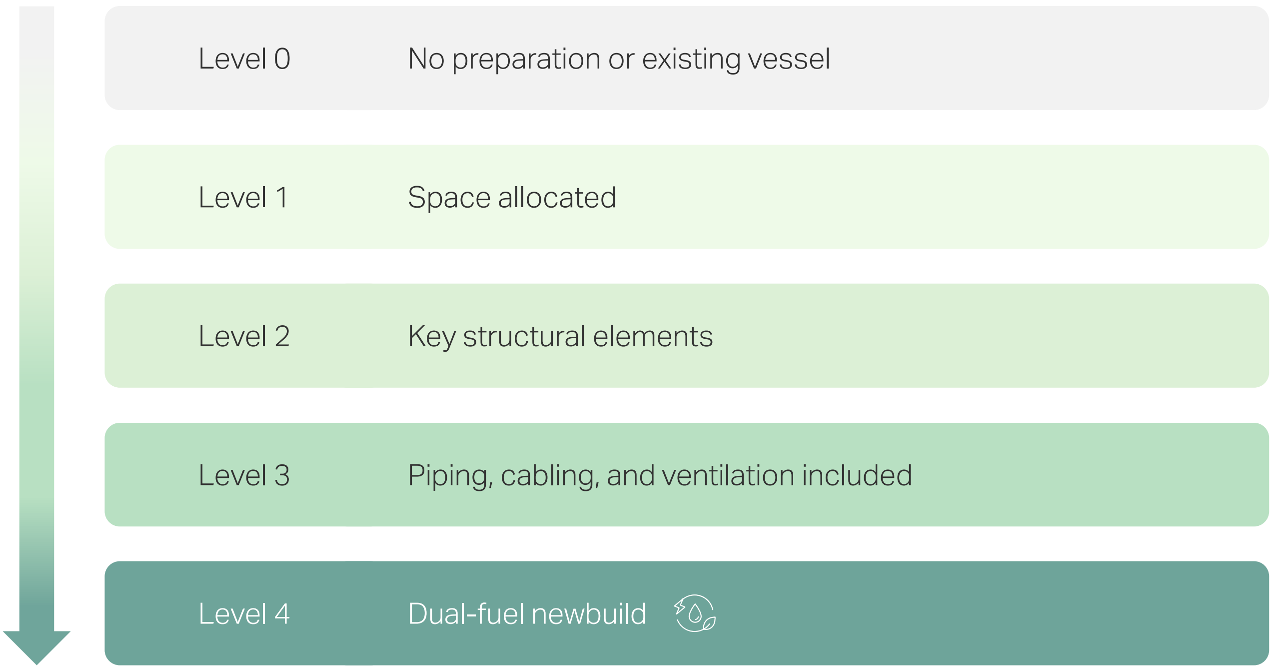
Vessel type	Range (NM)	Methanol	Ammonia	LNG
LR2	15,500	4,300 m^3	5,700 m^3	3,500 m^3
VLCC	14,000	9,000 m^3	11,600 m^3	11,600 m^3

LNG = liquefied natural gas.

2.3 Vessel preparation levels

As previously mentioned, vessels can be constructed at different levels of preparedness for fuel conversion. However, it can be challenging to determine which level of preparation provides the optimal balance of upfront costs, conversion costs, and reduced cargo capacity. Therefore, our study considered five different levels of vessel preparation for operation on alternative fuels, from no preparation or existing conventional vessel (Level 0) to a fully dual-fuel vessel (Level 4). These levels are summarized in Figure 2. A more detailed description of relevant features of each preparation level is provided in the upcoming sections focusing on specific vessel types.

Figure 2: Summary of newbuild preparation levels for future fuel conversion.



2.4 Techno-economic assessment

The techno-economic assessment presented in this report is designed to address the dilemma for a shipowner who is about to build a new tanker vessel and must decide how to prepare the vessel for future fuel options. Should the vessel be ready to use an alternative fuel immediately, or simply prepared for future fuel conversion — and, if so, at what level?

For this project, we calculated the total cost (including from lost cargo capacity) over the full lifetime of reference vessels with different preparation levels and conversion timings since newbuild. Our reference tanker designs are based on existing designs, with the same tank arrangements for newbuild and retrofitted vessels. This means that full-range newbuilds are compared with full-range conversions, and similarly reduced-range newbuilds are compared with reduced-range conversions. To facilitate comparison of the different options, the costs included in our model are all present-value and include:

- Add-on costs for preparing a dual-fuel or conversion-ready vessel (compared to a conventional vessel (Level 0))
- Costs related to reduced cargo capacity in the period from newbuild until conversion or until 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 conversion and for the rest of the vessel's lifetime
- Costs associated with future conversion
- Assumed fuel cost savings related to operation on LNG before conversion (for LNG to ammonia conversion only)

These costs are calculated for each year from newbuilding until the end of the vessel's lifetime, allowing the total costs (capital expenditure (CapEx) and cargo loss value) to be compared across all preparation levels year by year. We assume a 7% interest rate but do not account for inflation. The fuel spread between fuel oil and LNG is assumed to be 140 USD/tonne fuel oil equivalent, based on recent figures in a 'normal' fuel market (i.e., before COVID and sanctions against Russia).

Operating expenses related to future fuel prices for methanol and ammonia or from carbon tax schemes are not included in the model, as these figures are currently highly uncertain. Resale value of vessels is also excluded from our analysis. Off-hire costs related to fuel conversion are not included, but their impact is illustrated by a sensitivity analysis.

The cost estimates used in the model are based on the experience and insight of project participants and are to be considered as should-cost estimates. We assume that no major hull strengthening is required as part of conversion. We have identified the major cost items as: main and auxiliary engine conversion, tank systems, fuel supply system and piping, and yard installation work. The basis for estimating these costs is summarized in Table 3.

Table 3: Sources of cost estimates for techno-economic model of fuel conversion.

Cost	Basis for cost estimates
Conversion of main engine, auxiliary engines, and boiler	Provided by project partners
Fuel tank	Market insight from partners Calculations based on tank size and steel and labor costs
Coating for methanol tanks	Insight from project partners
Fuel supply systems	Supplier input
Yard installation	Experience of project partners

Our estimated newbuild and conversion costs assume that engine and conversion costs for conversion to methanol or ammonia are comparable to those for conversion to LNG or LPG. This assumption may change based on the further technological development of methanol and ammonia engines, boilers, machinery, and supply systems.

Actual conversion costs will depend on the geographic location and the specific yard where the conversion takes place. Actual material prices, market situation, yard contingency levels, and the commercial project model (turnkey, fixed-price, cost + mark-up, or time-and-material) can all have a large impact on the final price.

Using these estimates and information, we developed an Excel-based assessment model for total cost calculations. The results of our model are framed in terms of the present value (PV) of total conversion cost depending on time from newbuild to conversion.

2.5 Greenhouse gas emissions analysis

The main objective of switching from conventional to alternative fuels is to reduce GHG emissions and comply with future environmental regulations. Therefore, it is essential to assess the climate impacts of these fuel conversion options. Our GHG emissions analysis in this report focuses on comparing emissions during the vessel's operational lifetime both before and after fuel conversion.

We analyzed emissions during vessel operation using two timescales: conversion after five years and after ten years. We have chosen these timescales because methanol and ammonia are expected to be available at a limited scale within five years, with wider availability following in ten years if critical levers, including a global carbon levy, are activated. One would also typically carry out a conversion of a vessel on a five- or ten-yearly survey window of the asset.

Details of the assumptions, equations, and GHG emissions figures used in this analysis are available in Section 2.3 of our previous report on Preparing Container Vessels for Conversion to Green Fuels. We derived our information primarily from IMO documentation and from the total cost of ownership calculator in the MMMCZCS's techno-economic model.[7] Readers should note that our calculations of GHG emissions from methanol- and ammonia-fueled operations are based on net-zero e-methanol and e-ammonia used with fossil pilot fuel. Therefore, they represent a relatively optimistic but realistic emissions reduction scenario.

7 NavigaTE To Zero: Modeling of the maritime decarbonization, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021.

03 Fuel oil to methanol conversions

In this section, we present our proposed designs for dual-fuel or conversion-ready tanker vessels intended for use with fuel oil and methanol. Both full-range and reduced-range designs are considered. We provide a techno-economic analysis of the total costs of conversion from fuel oil to methanol depending on conversion timeline, desired range, and newbuild preparation levels. Based on these results, we recommend newbuild preparation levels based on desired range and conversion timeline, allowing intelligent newbuild design and preparation for future fleet planning.

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

This section outlines key design considerations for methanol-fueled tanker vessels and how we approached these considerations in our final designs. The first key consideration is the location and arrangement of the fuel tanks. Interim guidelines from the IMO state that integral methanol fuel tanks must be bounded by cofferdams, except where the fuel tank is bounded by other tanks containing methanol or ethanol, areas below the lowest possible water line, and the fuel preparation space.[8]
A cofferdam is a structural space that surrounds a fuel tank and acts as a gas- and liquid-tight secondary barrier between the tank and adjacent areas.

For our tanker reference designs, methanol fuel tanks were arranged on deck where possible. This proved to be feasible for the LR2 designs (Figures 3 and 4) and the reduced-range VLCC design (Figure 6); however, space in the cargo hold was required for fuel storage in the full-range VLCC design (Figure 5). For this last design, we chose to use independent prismatic steel tanks installed in the cargo hold, as independent tanks can be installed more quickly when the ship is being converted. As part of this process, it is preferable where possible to use prefabricated tanks internally coated with zinc silicate and already equipped with internal outfitting, such as pumps, measuring instruments, and attached tank connection space.

We chose to locate open-type bunker stations on the port and starboard sides with parallel body line sufficiently contacted with the bunker barge.

8 Interim Guidelines for the safety of ships using methyl/ethyl alcohol as a fuel, International Maritime Organization (IMO), 2020.

3.1.1 Full-range LR2 design

Figure 3 shows a simplified version of our reference design for a methanol-fueled full-range LR2 tanker.

The full-range LR2 vessel needs a methanol storage capacity of around 5,400 m³ to retain the same range when using methanol as when using fuel oil. In our design, the methanol is stored on deck in IMO Type C tanks. Due to visibility requirements specified in the International Convention for the Safety of Life at Sea (SOLAS), it is not possible to install two 2,700 m³ tanks without increasing the height of the accommodation.[9] Therefore, our design uses four fuel tanks of 1,350 m³ each (Figure 3). A possible alternative would have been to install a taller accommodation block at the newbuilding stage, but we did not further investigate this option as it is unrepresentative of the current conventional fleet.

In this methanol conversion for the LR2, we consider the on-deck fuel tanks to have minimal impact on the standard parcel size and cargo capacity.

Methanol bunkering stations are located at midship both portside and starboard, near the cargo and fossil fuel manifolds.

3.1.2 Reduced-range LR2 design

Figure 4 shows a simplified version of our reference design for a methanol-fueled reduced-range LR2 tanker.

In formulating this design, we were guided by the range of LNG-fueled Aframax and LR2 tankers recently built or ordered. For these vessels, a storage capacity of 3,500 m³ of LNG appears to be the 'new normal' accepted by major charterers and operators. This storage capacity equates to a range of about 15,500 NM when running on LNG.

To target a similar range, a methanol-fueled ship requires 4,300 m³ of fuel storage. This requirement can be fulfilled in compliance with SOLAS using a pair of 2,150 m³ IMO Type C tanks. As with the full-range LR2 design, the tanks are located on the deck and so cargo volume capacity is not affected. The location of the methanol bunkering stations is the same as for the full-range design.

Figure 3: Simplified design for methanol-fueled LR2 tanker vessel with full range.

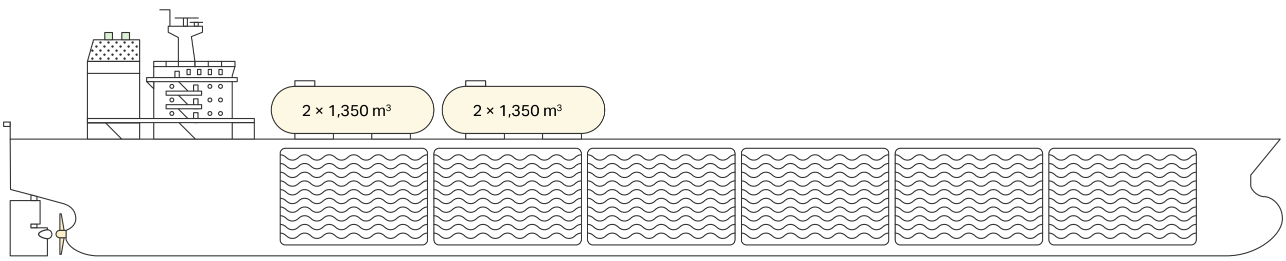
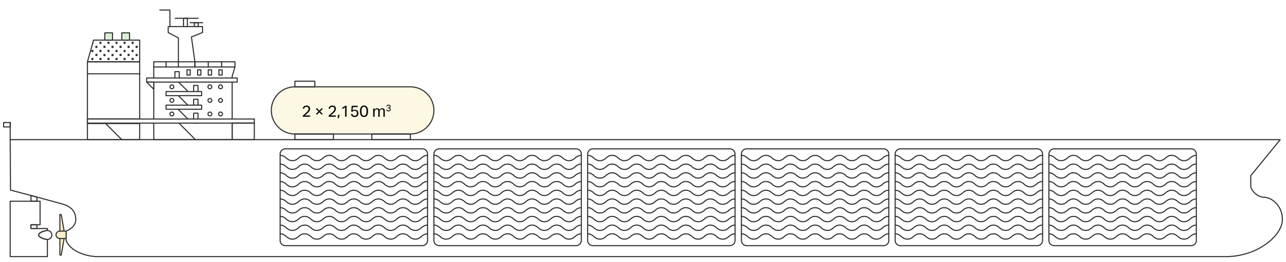


Figure 4: Simplified design for methanol-fueled LR2 tanker vessel with reduced range.



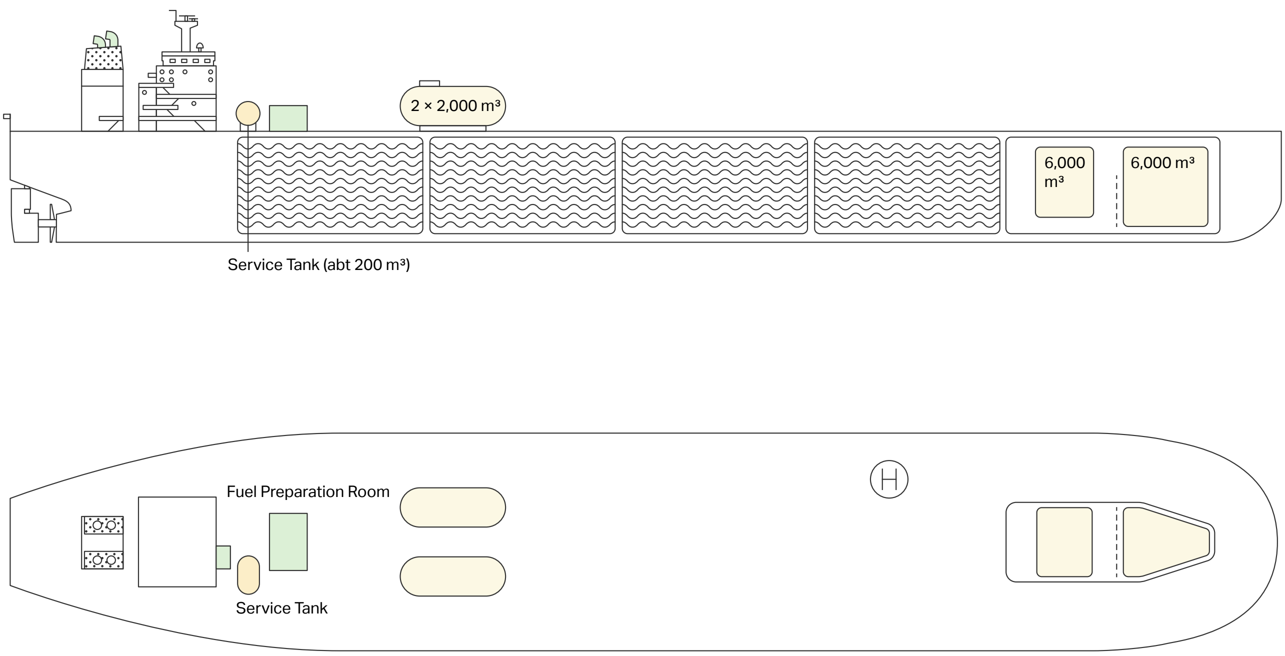
9 International Convention for the Safety of Life at Sea (SOLAS) Chapter V, Regulation 22 – Navigational bridge visibility, IMO, 1974 (as amended).

3.1.3 Full-range VLCC design

Figure 5 shows a simplified version of our reference design for a methanol-fueled full-range VLCC tanker.

The full-range VLCC vessel needs a methanol storage capacity of at least 15,900 m³ to retain the same range when using methanol as when using fuel oil. Due to SOLAS visibility requirements and interference with other processes such as helicopter operation, it is not possible to install five 3,000 m³ and one 1,000 m³ IMO Type C tanks on deck. Therefore, the fuel tanks for this design are a combination of IMO Type C tanks on deck and structural tanks in the cargo space. As with the LR2 vessel, we did not consider installation of taller accommodation at newbuild. As a result, this vessel design will lose cargo tank capacity when converted to methanol with full range.

Figure 5: Simplified design for methanol-fueled VLCC tanker vessel with full range.



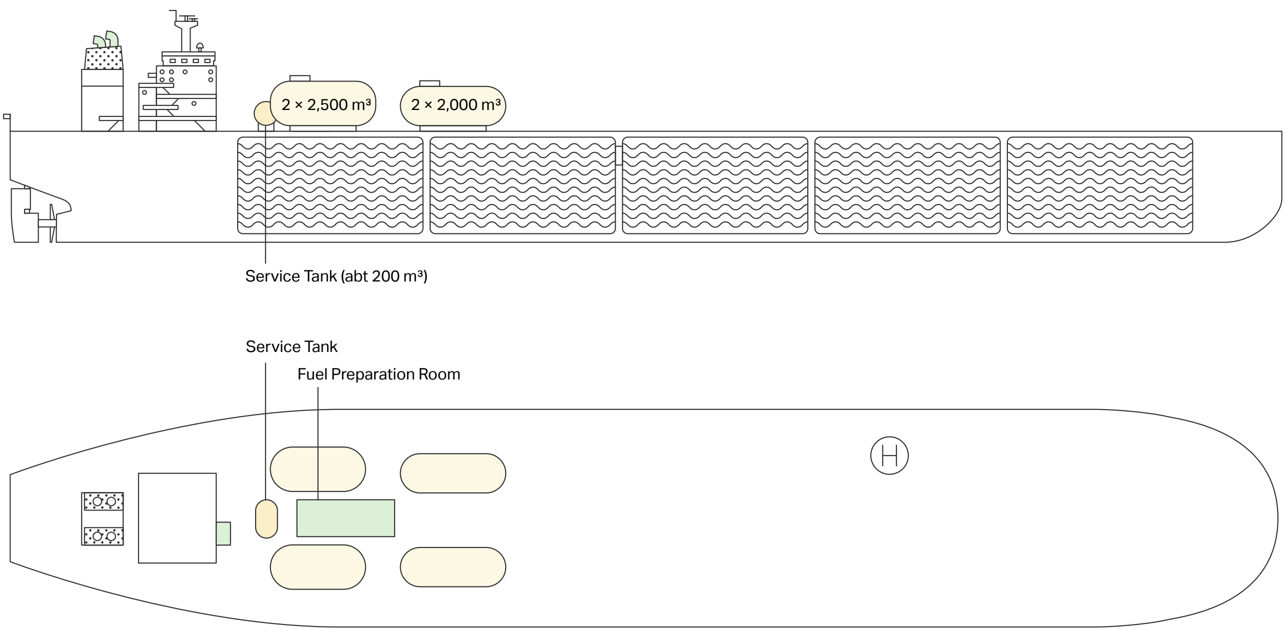
3.1.4 Reduced-range VLCC design

Figure 6 shows a simplified version of our reference design for a methanol-fueled reduced-range VLCC tanker.

In formulating this design, similar to the LR2 design, we were guided by the range of LNG-fueled VLCC vessels recently designed and ordered, which generally do not retain the range of equivalent vessels running on fuel oil. As covered in Table 2, we selected a target range of approximately 14,000 NM for this design.

To retain this target range, a methanol-fueled vessel requires 9,000 m³ of fuel storage. In our design, this is fulfilled by two 2,500 m³ IMO Type C tanks and two 2,000 m³ IMO Type C tanks located on the deck.

Figure 6: Simplified design for methanol-fueled VLCC tanker vessel with reduced range.



3.2 Preparation levels for methanol-ready newbuilds

Based on the designs outlined above and our assessment of which preparations will have the greatest impact on reducing complexity of future fuel conversions, we propose the following preparation levels for newbuilds that can be converted from fuel oil to methanol (summarized in Table 4). For additional reference, preparation level 0 is a conventional vessel with no preparation for methanol fuel, and preparation level 4 is a methanol-fuel oil dual-fuel vessel.

Even if the vessel is only built at preparation level 1, all methanol design principles (outlined in Section 3.1) must be considered, and initial designs for conversion must be completed at the newbuild stage to allow sufficient space allocation and successful later conversion.

Table 4: Description of preparation levels for newbuild tankers to be converted from fuel oil to methanol.

	Prep level 1	Prep level 2	Prep level 3
Bunker station	Space allocated at midship (port and side)	Space allocated at midship (port and side) Bunker lines routing prepared (supports and trunks)	As level 2
Tank	Space allocated	Space allocated Deck reinforced for methanol tanks	As level 2
Fuel preparation room	Space allocated	Room constructed	As level 2
Fuel supply system (including piping)	Space allocated	Space allocated	Space allocated Piping toward machinery installed
Main engine	Maker and engine bore to be chosen for possible later conversion	As level 1	As level 1
Auxiliary engines and boiler	Maker and model to be chosen for possible later conversion	As level 1	As level 1
Ventilation	Space allocated	As level 1	As level 1
Safety equipment	Space allocated	Space allocated Upgrade of water/safety pump capacity	Space allocated Upgrade of water/safety pump capacity and main piping fitted
Electrical installations	Space allocated (possible extension of switchboard included)	As level 1	Spare breakers and busbars installed Main cable tray fitted
Vent mast	Space allocated	Deck reinforcement for future vent mast installation	As level 2
General	Trim, stability, and longitudinal strength to be considered for future conversion	Trim, stability, and longitudinal strength to be considered for future conversion Risk analysis to be carried out	As level 2

3.3 Techno-economic analysis of fuel oil to methanol conversions

3.3.1 CapEx

Tables 5 and 6 show the estimated CapEx investments for newbuilding and conversion for each vessel design and preparation level outlined in Sections 3.1 and 3.2. The CapEx is formulated in terms of percentage of newbuild cost (% NB cost) of a standard vessel running on fuel oil. The cost of a fully dual-fuel newbuild (preparation level 4) is uncertain, as no typical real-world values exist. We estimated these costs based on the assumption of a mature market. The data for the cost assumptions were collected during 2022.

Table 5: CapEx estimates for conversion of LR2 tanker vessel from fuel oil to methanol.

LR2 tanker fuel oil-methanol conversion CapEx — full range					
	Prep level 0 (% of NB cost)	Prep level 1 (% of NB cost)	Prep level 2 (% of NB cost)	Prep level 3 (% of NB cost)	Prep level 4 (% of NB cost)
Prep cost	0%	1%	1%	2%	15%
Conversion cost	27%	25%	23%	21%	n/a
Total cost	27%	26%	24%	23%	15%

LR2 tanker fuel oil-methanol conversion CapEx — reduced range					
	Prep level 0 (% of NB cost)	Prep level 1 (% of NB cost)	Prep level 2 (% of NB cost)	Prep level 3 (% of NB cost)	Prep level 4 (% of NB cost)
Prep cost	0%	1%	1%	2%	14%
Conversion cost	26%	24%	23%	20%	n/a
Total cost	26%	25%	24%	22%	14%

NB = newbuild, n/a = not applicable.

Table 6: CapEx estimates for conversion of VLCC tanker vessel from fuel oil to methanol.

VLCC fuel oil-methanol conversion CapEx — full range					
	Prep level 0 (% of NB cost)	Prep level 1 (% of NB cost)	Prep level 2 (% of NB cost)	Prep level 3 (% of NB cost)	Prep level 4 (% of NB cost)
Prep cost	0%	1%	2%	5%	21%
Conversion cost	34%	32%	29%	25%	n/a
Total cost	34%	33%	31%	30%	21%

VLCC fuel oil-methanol conversion CapEx — reduced range					
	Prep level 0 (% of NB cost)	Prep level 1 (% of NB cost)	Prep level 2 (% of NB cost)	Prep level 3 (% of NB cost)	Prep level 4 (% of NB cost)
Prep cost	0%	1%	2%	5%	17%
Conversion cost	29%	27%	24%	20%	n/a
Total cost	29%	28%	26%	24%	17%

NB = newbuild, n/a = not applicable.

3.3.2 Total cost

In this section, we present estimates of the total cost of fuel oil-methanol conversion for our four reference designs. This assessment includes the cost of lost cargo capacity before and after conversion. Results are presented as present value (PV) of the cost depending on time since newbuild.

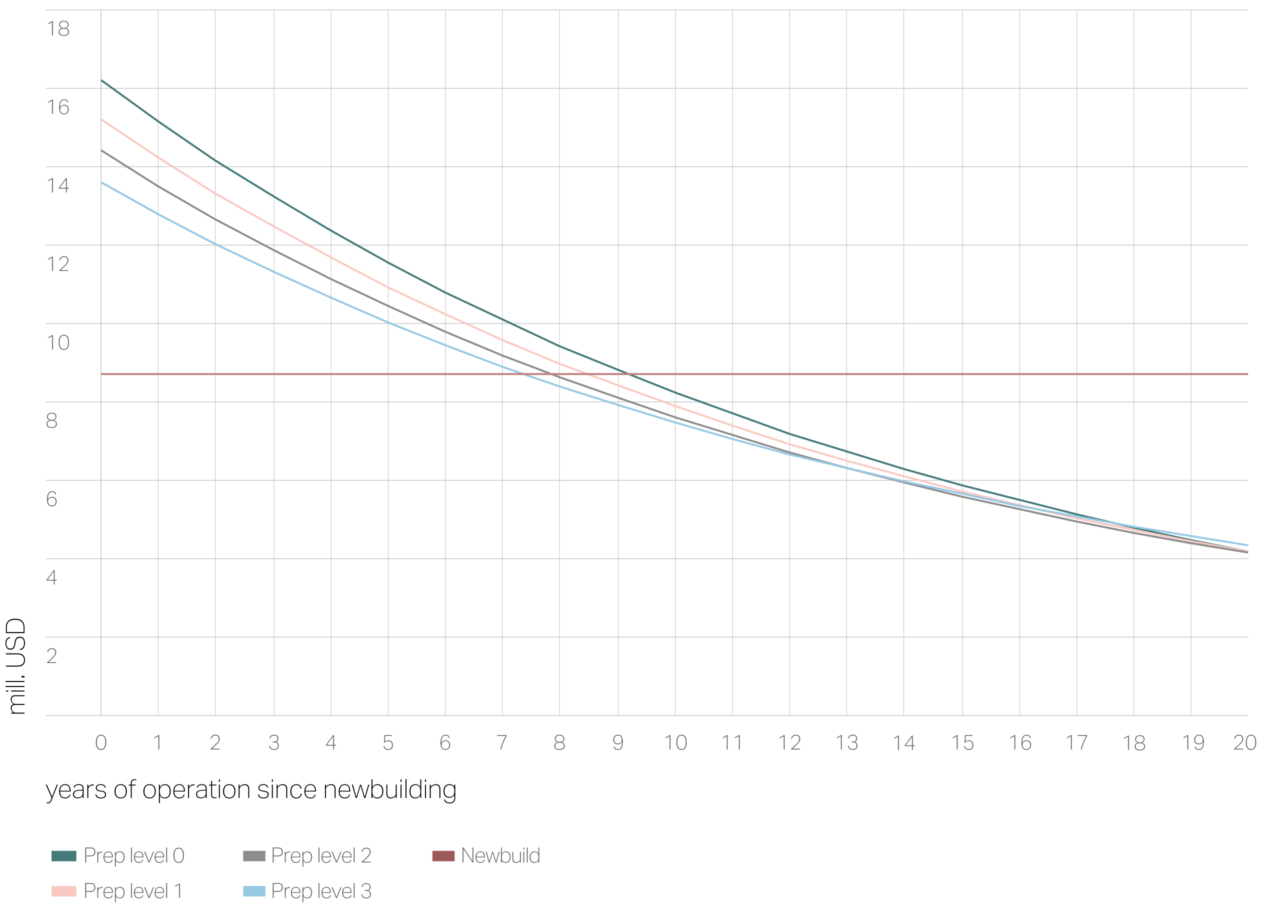
Figure 7 shows the PV total cost of conversion from fuel oil to methanol for a full-range LR2 tanker vessel. The equivalent figures for the other three vessel designs are provided in the Appendix.

As shown in Figure 7, if the full-range LR2 vessel begins operating on methanol 0-7 years after newbuild, the least expensive option is to build the vessel as a dual-fuel newbuild (brick red line). If conversion to methanol operation is planned 7-14 years after newbuild, the least expensive option is to build the vessel at preparation level 3 (blue line). If methanol operation is planned after 14 years, preparation level 2 (gray line) is the least expensive option. This being said, the total cost difference between different preparation levels is fairly small after ten years of operation and minimal after 15 years. The relevance of converting an LR2 at an age of 14 years or older should, of course, be considered as well.

For the reduced-range LR2 vessel, the least expensive option is a dual-fuel newbuild if the vessel will begin operating on methanol within 0-7.5 years. After 7.5-14 years, preparation level 3 is the least expensive option. After 14 years, preparation level 2 is the best option, with preparation level 1 close behind.

For the full-range VLCC vessel, a dual-fuel newbuild is the least expensive option if methanol operation begins within 1.5 years. After 1.5-9 years, preparation

Figure 7: Present value of total fuel oil-methanol conversion cost for a full-range LR2 tanker vessel.



level 3 is the least expensive option, and after more than nine years, preparation level 0 is the cheapest option, but very close to preparation level 1 and 2. However, fuel conversion for the full-range VLCC design is not commercially viable due to the resulting loss of cargo capacity, so these results are presented for informational purposes only.

Because the full-range VLCC design cannot be viably converted to methanol fuel, we compared our reduced-range VLCC vessel design with a reduced-range newbuild. A full-range newbuild would have a significantly higher total cost than a reduced-range converted vessel at any timepoint. For the reduced-range VLCC design, a dual-fuel newbuild is the least expensive option if methanol operation begins within 0-6 years. After 6-9 years, preparation level 3 is the least expensive option, and either preparation level 1 or 2 is the cheapest if methanol operation begins after nine years.

Table 7 summarizes our recommendations for tanker newbuild preparation levels based on these analyses of total cost. Our recommended preparation levels are based on the lowest total costs; however, shipowners should carefully consider what is right for them and their own individual circumstances when planning vessels and conversions.

Table 7: Recommendations for tanker vessel preparation levels for conversion from fuel oil to methanol based on present-value total cost and time since newbuild.

LR2 tanker, FO-methanol, full range conversion			
Years of operation since newbuild	0-7 years	7-14 years	14-20 years
Lowest PV cost option	DF methanol newbuild	Prep level 3	Prep level 2
LR2 tanker, FO-methanol, reduced range conversion			
Years of operation since newbuild	0-7.5 years	7.5-14 years	14-20 years
Lowest PV cost option	DF methanol newbuild	Prep level 3	Prep level 2
VLCC, FO-methanol, full range conversion			
Years of operation since newbuild	0-1.5 years	1.5-9 years	9-15 years
Lowest PV cost option	DF methanol newbuild	Prep level 3	Prep level 0
VLCC, FO-methanol, reduced range conversion (compared to reduced-range newbuild)			
Years of operation since newbuild	0-6 years	6-9 years	9-15 years
Lowest PV cost option	DF methanol newbuild	Prep level 3	Prep level 1 or 2

FO = fuel oil, PV = present value, DF = dual-fuel.

3.3.3 Sensitivity analysis

In addition to the main techno-economic analysis of total cost, we carried out a sensitivity analysis to better understand the impacts of cargo loss value and off-hire costs on the results.

The impact of cargo loss value is only relevant to the VLCC, as the DWT reduction due to conversion for the LR2 designs did not impact their maximum parcel size. We found that if the cargo value is doubled, the period for which a given preparation level is recommended is reduced by approximately 0.75 years. To illustrate, if the cargo value (and, therefore, the cost value of cargo loss) is doubled, the period for which a dual-fuel newbuild is the cheapest overall option is reduced from 1.5 years to 0.75 years for the full-range VLCC design.

Regarding the impact of off-hire costs, every 0.5 million USD in off-hire costs added to cost of conversion generally increases the break-even point between a dual-fuel newbuild and a conversion-ready newbuild by 0.5 years for LR2 vessels and 0.2 years for VLCC. Therefore, if a dual-fuel newbuild is nominally the cheapest option for the first 1.5 years, but 0.5 million USD in off-hire costs is added, this period increases to 2 years for an LR2 and 1.7 years for a VLCC.

04 Fuel oil to ammonia conversions

In this section, we present our proposed designs for dual-fuel or conversion-ready tanker vessels intended for use with fuel oil and ammonia. Both full-range and reduced-range designs are considered. We provide a techno-economic analysis of the total costs of conversion from fuel oil to ammonia depending on conversion timeline, desired range, and newbuild preparation levels. Based on these results, we recommend newbuild preparation levels based on desired range and conversion timeline, allowing intelligent newbuild design and preparation for future fleet planning.

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

As for methanol-fueled vessels, the location and arrangement of ammonia fuel tanks is a key consideration. For our LR2 and reduced-range VLCC designs, we opted for IMO Type C fuel tanks located on the deck. The full-range VLCC design requires either an additional prismatic IMO Type B tank or an IMO Type A tank in the cargo area. In this case, the requirement for a secondary barrier around the fuel tank can be met by using an appropriate grade of steel to construct the surrounding fuel storage space. If this is not possible, partial hull replacement of the relevant section to add a secondary barrier around the fuel tank is another option for achieving regulatory compliance. For our study, the full-range VLCC design includes a Type B fuel storage tank, and the lower part of the fuel storage space is constructed with compatible low-temperature-grade steel as a partial secondary barrier.

As for the methanol designs, we included open-type bunker stations on the port and starboard side with parallel body line in sufficient contact with the bunker barge.

4.1.1 Full-range LR2 design

A simplified version of our reference design for an ammonia-fueled full-range LR2 tanker is displayed in Figure 8.

The full-range LR2 vessel needs an ammonia storage capacity of at least 7,100 m³ to retain the same range when using ammonia as when using fuel oil. In our design, the ammonia is stored on deck in IMO Type C tanks. To comply with SOLAS visibility regulations, the design uses two 2,200 m³ tanks and two 1,350 m³ tanks (Figure 8).

4.1.2 Reduced-range LR2 design

A simplified version of our reference design for an ammonia-fueled reduced-range LR2 tanker is displayed in Figure 9.

In formulating this design, we were guided by the range of recent LNG-fueled tankers as described in Section 3.1.2. To target a range of 15,500 NM, an ammonia-fueled ship requires 5,700 m³ of fuel storage. Our design uses two 1,750 m³ IMO Type C tanks and two 1,100 m³ IMO Type C tanks, all located on the deck (Figure 9).

Figure 8: Simplified design for ammonia-fueled LR2 tanker vessel with full range.

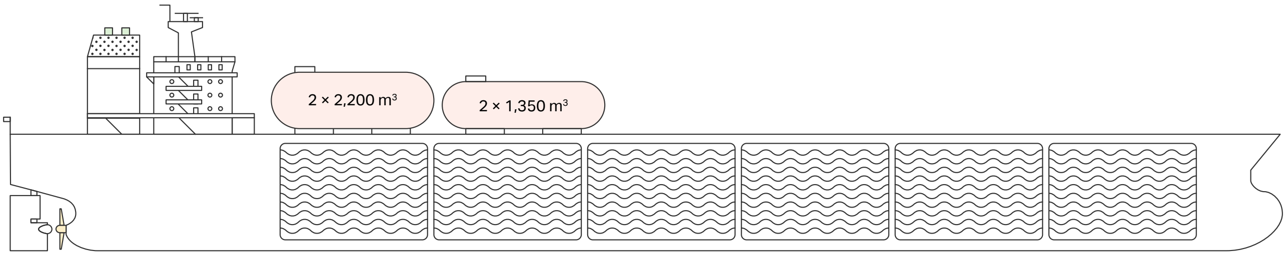
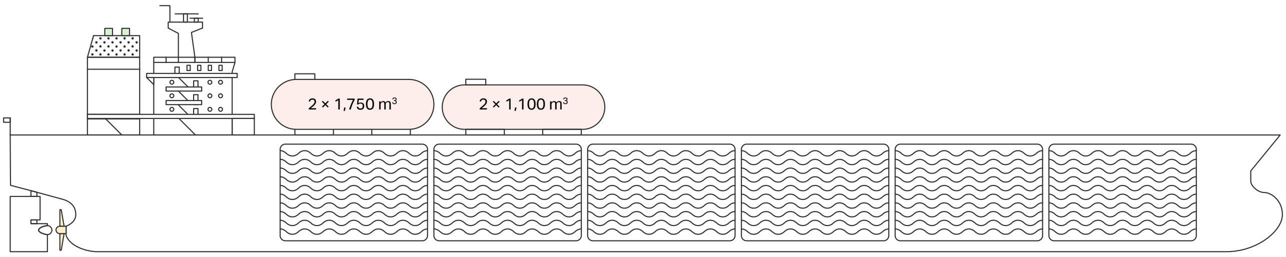


Figure 9: Simplified design for ammonia-fueled LR2 tanker vessel with reduced range.



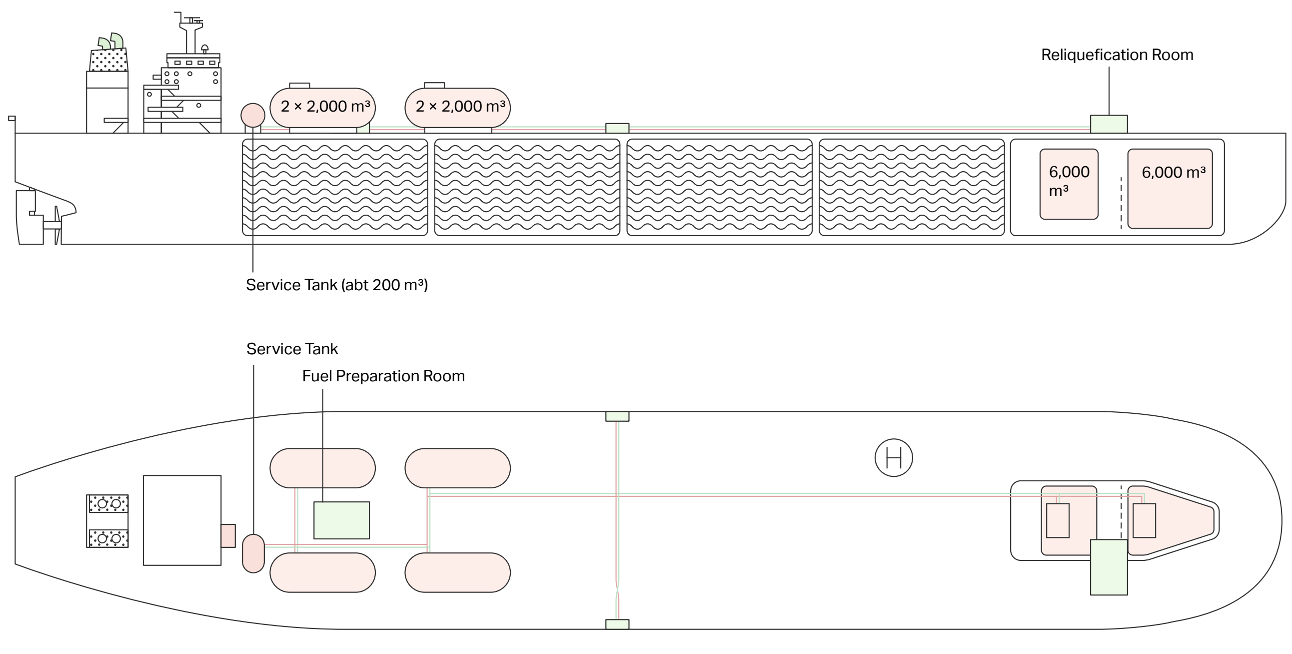
4.1.3 Full-range VLCC design

A simplified version of our reference design for an ammonia-fueled full-range VLCC tanker is displayed in Figure 10.

The full-range VLCC vessel needs an ammonia storage capacity of at least 19,800 m³ to retain the same range when using ammonia as when using fuel oil. In our design, this is achieved by locating four 2,000 m³ IMO Type C fuel tanks on the deck and two 6,000 m³ IMO Type B fuel tanks in one of the cargo tanks (Figure 10). Tanks in the cargo area must be arranged considering structural components such as the cross tie, horizontal girder, and swash bulkhead, and outfitting such as the cargo main line.

Similar to the full-range fuel oil to methanol conversions, the reduced cargo capacity for this design is not deemed commercially viable, but is again illustrated to show what would be necessary to maintain full range.

Figure 10: Simplified design for ammonia-fueled VLCC tanker vessel with full range.

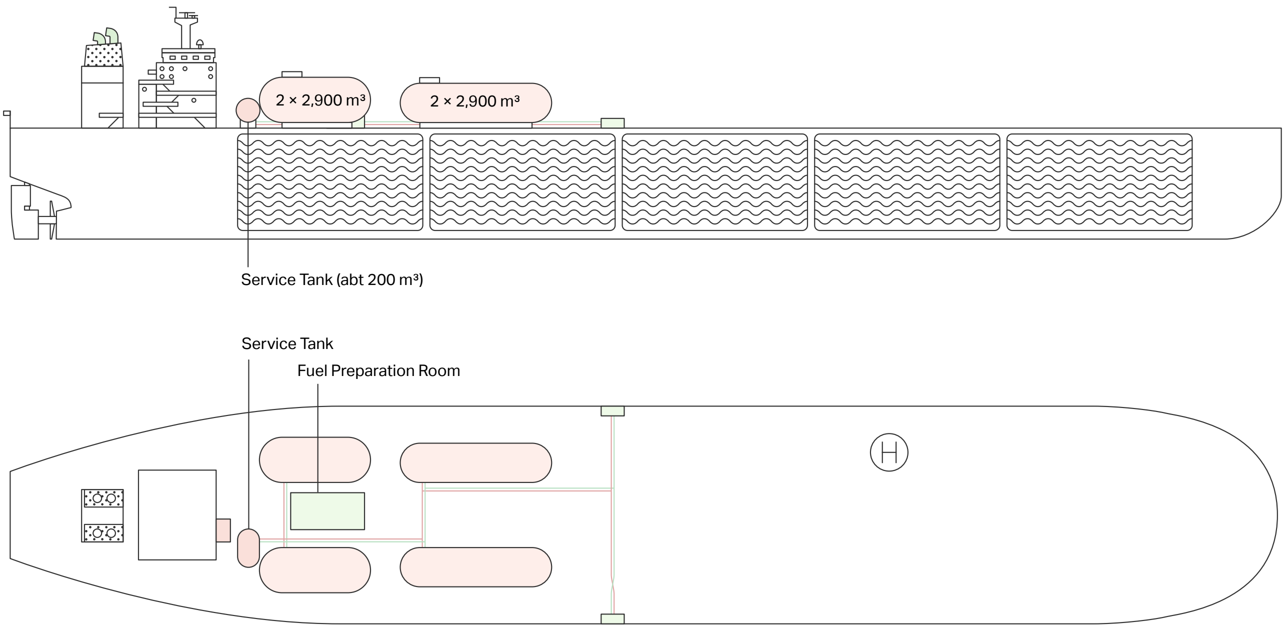


4.1.4 Reduced-range VLCC design

A simplified version of our reference design for an ammonia-fueled reduced-range VLCC tanker is displayed in Figure 11.

In formulating this design, we were guided by the requirements of the PG-FE trade route, as described in Section 2.2. To retain a range of 14,000 NM, an ammonia-fueled vessel requires 11,600 m^3 of ammonia fuel storage. In our design, this is fulfilled by four 2,900-m^3 IMO Type C tanks located on the deck.

Figure 11: Simplified design for ammonia-fueled VLCC tanker vessel with full range.



4.2 Preparation levels for ammonia-ready newbuilds

Based on the designs outlined above and our assessment of which preparations will have the greatest impact on reducing complexity of future fuel conversions, we propose the following preparation levels for newbuilds that can be converted from fuel oil to ammonia (summarized in Table 8). For additional reference, preparation level 0 is a conventional vessel with no preparation for methanol fuel, and preparation level 4 is a methanol-fuel oil dual-fuel vessel.

As ammonia is both toxic and flammable, special attention should be paid to safety during the planning and conversion of an ammonia-ready vessel. Examples of specific considerations include the identification of gas dangerous zones, installation of ammonia gas detection system(s), installation of eye wash and water spray systems, and internal coating of the ammonia solution collecting tank.

Table 8: Description of preparation levels for newbuild tankers to be converted from fuel oil to ammonia.

	Prep level 1	Prep level 2	Prep level 3
Bunker station	Space allocated at midship (port and side)	As level 1	As level 1
Tank	Space allocated Secondary barrier to be arranged, if necessary	As level 1, plus deck reinforced for ammonia tanks	As level 2
Fuel preparation room	Space allocated	Room constructed	As level 2
Fuel supply system (including piping)	Space allocated	As level 1	As level 1, plus piping toward machinery installed
Main engine	Maker and engine bore to be chosen for possible later conversion	As level 1	As level 1
Auxiliary engines and boiler	Maker and model to be chosen for possible later conversion	As level 1	As level 1
Ventilation	Space allocated	As level 1	As level 1
Safety equipment	Space allocated	As level 1, plus upgrade of water/safety pump capacity	As level 2, plus main piping fitted
Electrical installations	Space allocated (possible extension of switchboard included)	As level 1	As level 1, plus: Spare breakers and busbars installed Main cable tray fitted
Vent mast	Space allocated	Deck reinforcement for vent mast future installation	As level 2
General	Trim, stability, and longitudinal strength to be considered for future conversion	As level 1, plus risk analysis to be carried out	As level 2

4.3 Techno-economic analysis of fuel oil to ammonia conversions

4.3.1 CapEx

Tables 9 and 10 show the estimated CapEx investments for newbuilding and converting each vessel design and preparation level outlined in Sections 4.1 and 4.2. The CapEx is formulated in terms of percentage of newbuild cost (% NB cost) of a standard vessel running on fuel oil. As with fuel oil-methanol conversion, the cost of a fully dual-fuel newbuild has been estimated based on the assumption of a mature market (see Section 3.3.1).

Table 9: CapEx estimates for conversion of LR2 tanker vessel from fuel oil to ammonia.

LR2 tanker fuel oil-ammonia conversion CapEx — full range					
	Prep level 0 (% of NB cost)	Prep level 1 (% of NB cost)	Prep level 2 (% of NB cost)	Prep level 3 (% of NB cost)	Prep level 4 (% of NB cost)
Prep cost	0%	1%	1%	3%	27%
Conversion cost	42%	38%	36%	33%	n/a
Total cost	42%	39%	37%	37%	27%

LR2 tanker fuel oil-ammonia conversion CapEx — reduced range					
	Prep level 0 (% of NB cost)	Prep level 1 (% of NB cost)	Prep level 2 (% of NB cost)	Prep level 3 (% of NB cost)	Prep level 4 (% of NB cost)
Prep cost	0%	1%	1%	3%	25%
Conversion cost	41%	37%	35%	32%	n/a
Total cost	41%	38%	36%	35%	25%

NB = newbuild, n/a = not applicable.

Table 10: CapEx estimates for conversion of VLCC tanker vessel from fuel oil to ammonia.

VLCC fuel oil-ammonia conversion CapEx — full range					
	Prep level 0 (% of NB cost)	Prep level 1 (% of NB cost)	Prep level 2 (% of NB cost)	Prep level 3 (% of NB cost)	Prep level 4 (% of NB cost)
Prep cost	0%	1%	3%	6%	36%
Conversion cost	54%	49%	46%	40%	n/a
Total cost	54%	50%	49%	46%	36%

VLCC fuel oil-ammonia conversion CapEx — reduced range					
	Prep level 0 (% of NB cost)	Prep level 1 (% of NB cost)	Prep level 2 (% of NB cost)	Prep level 3 (% of NB cost)	Prep level 4 (% of NB cost)
Prep cost	0%	1%	3%	6%	31%
Conversion cost	45%	42%	39%	33%	n/a
Total cost	45%	43%	42%	39%	31%

NB = newbuild, n/a = not applicable.

4.3.2 Total cost

In this section, we present estimates of the total cost of fuel oil-ammonia conversion for our four reference designs. This assessment includes the cost of lost cargo capacity before and after conversion. Results are presented as present value (PV) of the cost depending on time since newbuild.

Figure 12 shows the present-value total cost of conversion from fuel oil to ammonia for a full-range LR2 tanker vessel. The equivalent figures for the other three vessel designs are provided in the Appendix.

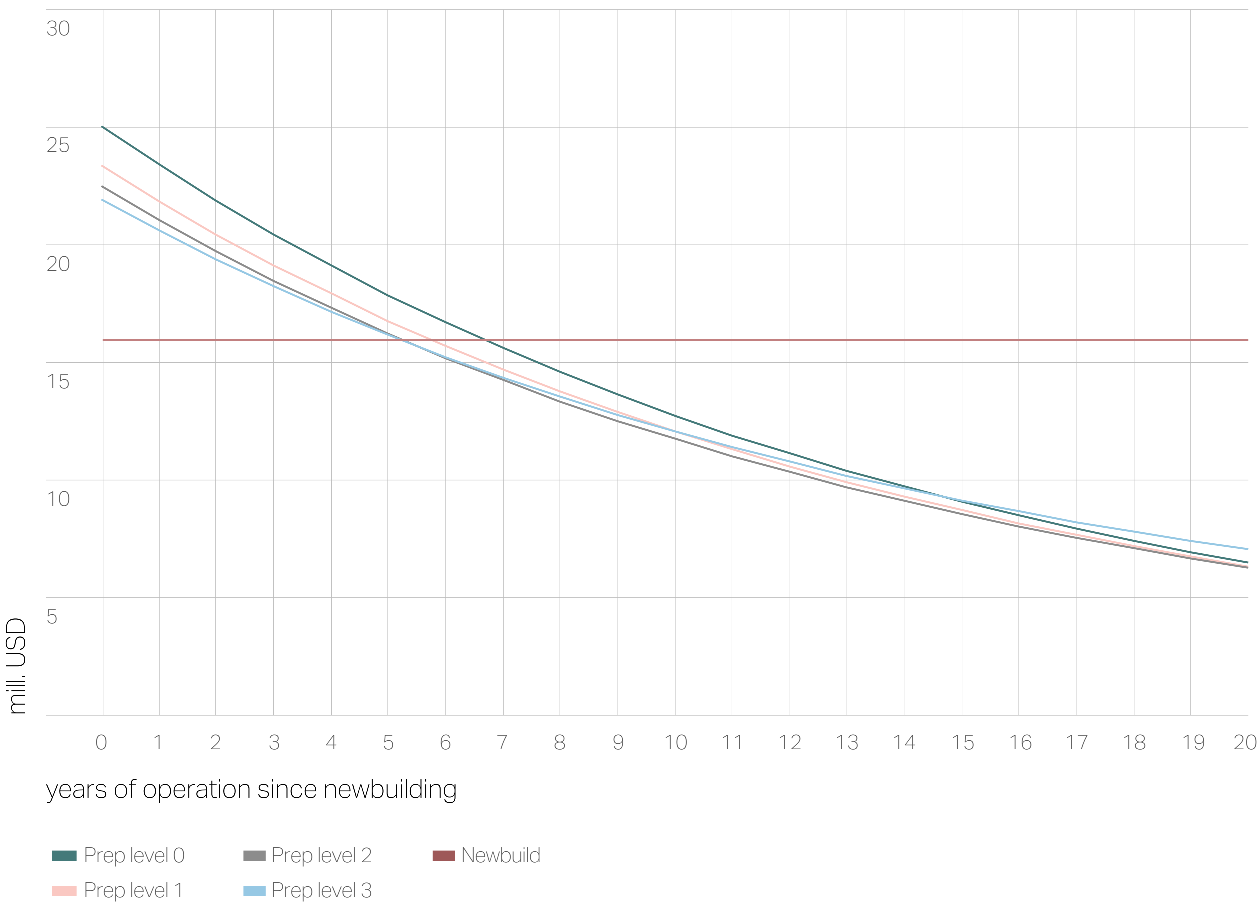
As shown in Figure 12, if the full-range LR2 vessel begins operating on ammonia 0-5 years after newbuild, a dual-fuel newbuild (brick red line) is the least expensive option. If the switch from fuel oil to ammonia operation is 5-20 years after newbuild, preparation level 2 (gray line) is the least expensive option. However, the cost difference between preparation levels is limited during the period 5-15 years after newbuilding. It could be argued that for conversions up to 10 years after newbuilding, selecting a higher preparation level, such as level 3, may reduce risk and time during installation.

For the reduced-range LR2 design, a dual-fuel newbuild is the least expensive option if operation on ammonia begins within 0-5.5 years. Beyond this time, preparation level 2 is the best option.

For the full-range VLCC design, a dual-fuel newbuild is the least expensive option if operation on ammonia begins within 0-1.5 years. After 1.5-8 years, preparation level 3 is the least expensive option. Preparation level 0, 1, or 2 is cheapest if the vessel switches to ammonia operation after 8-15 years.

For the reduced range VLCC a dual-fuel newbuild is the least expensive option if operation on ammonia begins within 0-4 years. After 4-8 years, preparation

Figure 12: Present value of total fuel oil-ammonia conversion cost for a full-range LR2 tanker vessel.



level 3 is the least expensive option. Preparation level 0, 1, or 2 is cheapest if the vessel switches to ammonia operation after 8-15 years.

Table 11 summarizes our recommendations for tanker newbuild preparation levels based on these analyses of total cost. As with the methanol case, shipowners should carefully consider their individual circumstances when planning vessels and conversions.

4.3.3 Sensitivity analysis

As with the fuel oil to methanol conversions, we carried out a sensitivity analysis to better understand the impacts of cargo loss value and off-hire costs on our results.

As in the methanol case, the impact of cargo loss value is only relevant to the VLCC. We found that if the cargo value is doubled, the period for which a given preparation level is recommended is reduced by approximately 0.5 years. To illustrate, if the cargo value (and therefore the cost value of cargo loss) is doubled, the period for which a dual-fuel newbuild is the cheapest overall option is reduced from 1.5 years to one year for the full-range VLCC design.

Every 0.5 million USD in off-hire costs added to cost of conversion generally increases the break-even point between a dual-fuel newbuild and a conversion-ready newbuild by 0.5 years for LR2 vessels and 0.2 years for VLCC. Please refer to Section 3.3.3 for an example calculation.

Table 11: Recommendations for tanker vessel preparation levels for conversion from fuel oil to ammonia based on present-value total cost and time since newbuild.

LR2 tanker, FO-ammonia, full range conversion			
Years of operation since newbuild	0-5 years	5-20 years	—
Lowest PV cost option	DF ammonia newbuild	Prep level 2	—
LR2 tanker, FO-ammonia, reduced range conversion			
Years of operation since newbuild	0-5.5 years	5.5-20 years	—
Lowest PV cost option	DF ammonia newbuild	Prep level 2	—
VLCC, FO-ammonia, full range conversion			
Years of operation since newbuild	0-1.5 years	1.5-8 years	8-15 years
Lowest PV cost option	DF ammonia newbuild	Prep level 3	Prep level 0/1/2
VLCC, FO-ammonia, reduced range conversion			
Years of operation since newbuild	0-4 years	4-8 years	8-15 years
Lowest PV cost option	DF ammonia newbuild	Prep level 3	Prep level 0/1/2

FO = fuel oil, PV = present value, DF = dual-fuel

05 LNG to ammonia conversions

In this section, we provide proposed designs for converting the LR2 and VLCC tankers from LNG-fuel oil to ammonia-fuel oil. Conversion from LNG to ammonia is somewhat different from converting from fuel oil, as many of the gas fuel handling arrangements required for ammonia are also required for LNG. 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.

Conversion from LNG to ammonia raises several additional parameters that can impact the feasibility and attractiveness of conversion. These include:

- Whether the vessel's range can meet commercial needs, as the same tank capacity provides about 40% lower range when using ammonia compared to LNG
- Compatibility of materials with both cryogenic temperatures and ammonia corrosion
- Definition of hazardous areas (explosion and toxicity) for each fuel
- Compliance with both established regulatory requirements for LNG and evolving regulatory guidelines for ammonia fuel

In this section, we compare the total cost for converting a prepared LNG-fueled vessel to ammonia with an ammonia-fuel oil dual-fuel newbuild. As the reference fuel here is not the same as for the fuel oil-ammonia conversion described in Section 4 (fuel oil versus LNG), an assumed fuel oil-LNG saving of 140 USD/tonne fuel oil equivalent is included in the total cost calculations. This value is based on traditional market conditions (i.e., prior to the COVID-19 pandemic and war in Ukraine).

Both a full-range and a reduced-range design were considered for the LR2 tanker. We also chose to include a third, 'limited-range' LR2 design with an even smaller range than the reduced-range design (see Section 5.1.3) as an additional plausible option. We considered only a reduced-range conversion for the VLCC, as the full-range design was not deemed commercially feasible when operating on ammonia (Section 4).

Based on the results of our techno-economic analysis, we recommend newbuild preparation levels based on desired range (where applicable) and conversion timeline, allowing intelligent newbuild design and preparation for future fleet planning.

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

As for previous sections, fuel storage is a key design consideration. Large cryogenic fuel tanks are often made of 9% nickel steel (9% Ni steel); however, this material is not compatible with ammonia. Therefore, a vessel intended for conversion from LNG to ammonia must either use stainless-steel LNG storage tanks or replace 9% Ni steel LNG storage tanks with low-temperature steel ammonia storage tanks during conversion.

For the purposes of our study, the latter option was selected for preparation levels 0 and 1 in the LR2 case. For the LR2 designs, we also included replacement of LNG storage tanks with appropriate ammonia storage tanks as part of the conversion process for vessels built at preparation level 1, since additional ammonia tanks must be installed regardless in order to maintain the vessel's range after conversion.

For the VLCC, we have assumed that ammonia-ready tanks (stainless steel) are installed from prep level 1, as the LNG capacity equals the reduced-range ammonia capacity, and no additional tanks will be installed when converting to ammonia.

5.1.1 Full-range LR2 design

Simplified versions of our reference designs for LNG- and ammonia-fueled full-range LR2 tankers are displayed in Figures 13 and 14, respectively.

The full-range LR2 vessel needs an LNG storage capacity of at least 4,400 m³ to retain the same range when using LNG as when using fuel oil. In our design, the LNG is stored on deck in two 2,200 m³ IMO Type C tanks. Retaining the same range when using ammonia requires an additional 2,700 m³ of fuel storage, which our design fulfils by adding two 1,350 m³ IMO Type C tanks located on the deck.

Figure 13: Simplified design for LNG-fueled LR2 tanker vessel with full range.

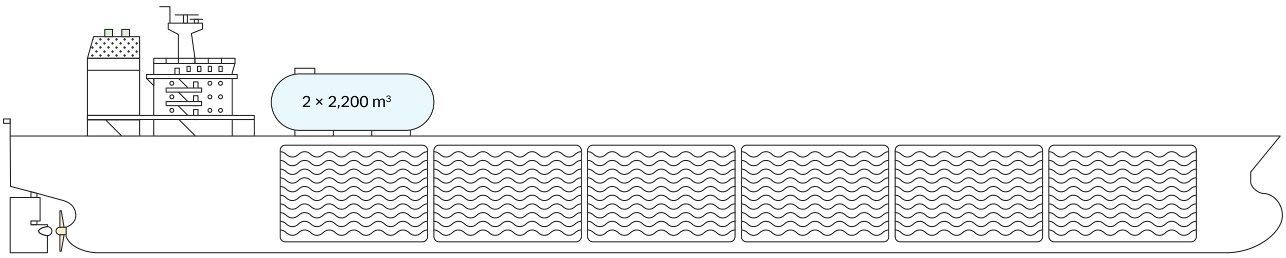
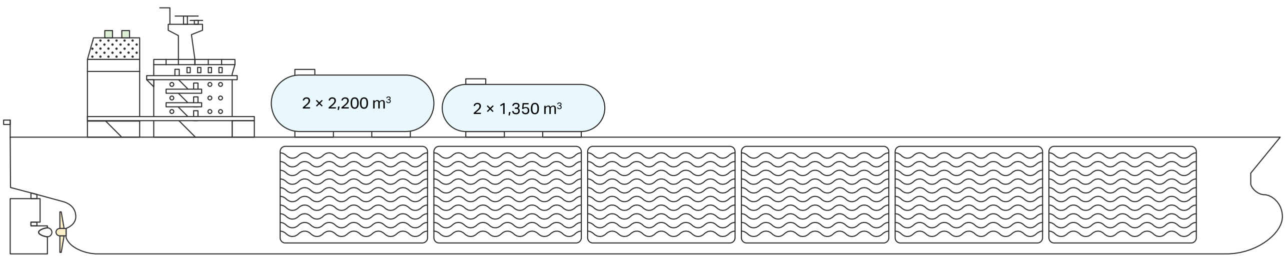


Figure 14: Simplified design for ammonia-fueled LR2 tanker vessel with full range (converted from LNG-fueled design in Figure 13).



5.1.2 Reduced-range LR2 design

Simplified versions of our reference designs for LNG-fueled and ammonia-fueled reduced-range LR2 tankers are displayed in Figures 15 and 16, respectively.

In formulating this design, we were guided by the range of recent LNG-fueled tankers as described in Section 3.1.2. To target a range of 15,500 NM, an LNG-fueled ship requires 3,500 m³ of storage capacity, which is fulfilled in our design with two on-deck IMO Type C tanks of 1,750 m³ each (Figure 15). To target the same range, an ammonia-fueled ship requires an additional 2,200 m³ of fuel storage. For this, our design uses an additional pair of on-deck 1,100 m³ IMO Type C tanks (Figure 16).

5.1.3 Limited-range LR2 design

In addition to the reduced-range LR2 design described in Section 5.1.2, we considered a case of LNG to ammonia conversion with an even greater range reduction, which we term the limited-range LR2 design. This design retains the same fuel storage capacity and tank arrangement as the reduced-range LNG-fueled design (Figure 15) when operating on ammonia, resulting in a range reduction of 10,000 NM compared to operation on fuel oil. This design is a relevant option, because it allows for a simpler conversion in cases where 100% operation on ammonia is not required in the initial phase.

Figure 15: Simplified design for LNG-fueled LR2 tanker vessel with reduced range.

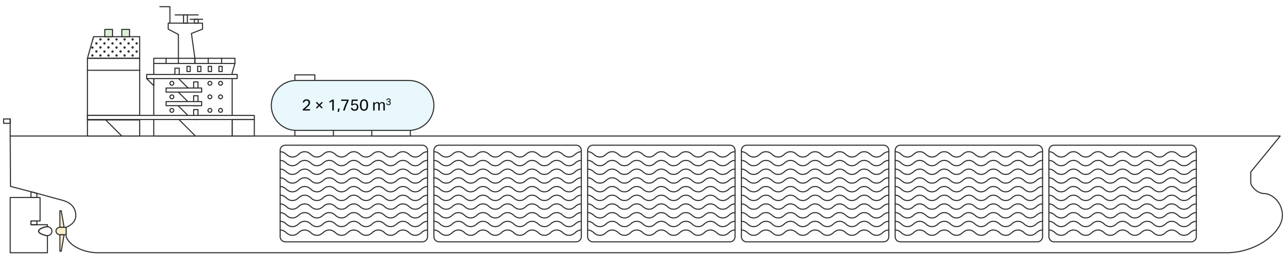
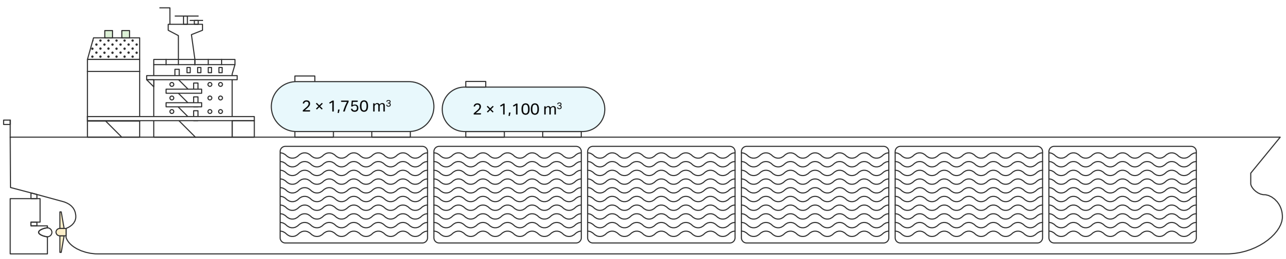


Figure 16: Simplified design for ammonia-fueled LR2 tanker vessel with reduced range (converted from LNG-fueled design in Figure 15).

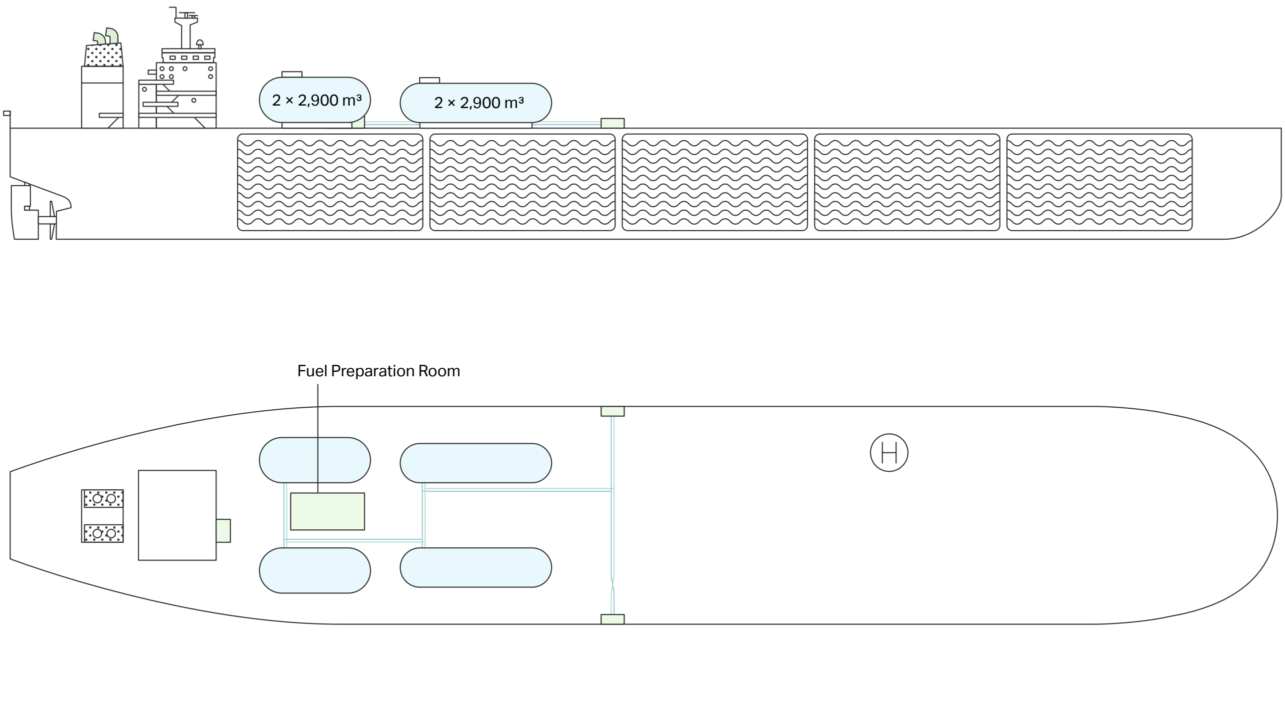


5.1.4 Reduced-range VLCC design

A simplified version of our reference design for an ammonia-fueled reduced-range VLCC tanker converted from LNG operation is displayed in Figure 17.

In formulating this design, we were guided by the requirements of the PG-FE trade route, as described in Section 2.2. To retain a range of 14,000 NM, an ammonia-fueled vessel requires 11,600 m³ of fuel storage. As this is almost the same fuel storage capacity required to maintain the range of a fuel oil VLCC vessel using LNG, we have assumed the same tank capacity and arrangement before and after conversion from LNG to ammonia operation. The design has four 2,900-m³ IMO Type C tanks located on the deck (Figure 17). We have assumed that these will be ammonia-ready LNG tanks (see Table 12).

Figure 17: Simplified design for VLCC tanker vessel with reduced range when using ammonia (converted from full-range LNG operation).



5.2 Preparation levels for ammonia-ready newbuilds

Based on the designs outlined above and our assessment of which preparations will have the greatest impact on reducing complexity of future fuel conversions, we propose the following preparation levels for newbuilds that can be converted from LNG to ammonia (summarized in Table 12). For additional reference, preparation level 0 is a conventional vessel with no preparation for ammonia fuel, and preparation level 4 is an ammonia-fuel oil dual-fuel vessel.

Many fundamental requirements for gaseous fuels are already included in LNG-fueled designs, simplifying the conversion from LNG to ammonia fuel. Designs must ensure that physical installations, piping, and ventilation systems have the correct dimensions for use with ammonia. As mentioned in Section 4.2, special attention to safety measures is required based on ammonia's toxic and flammable properties.

Table 12: Description of preparation levels for newbuild tankers to be converted from LNG to ammonia.

	Prep level 1	Prep level 2	Prep level 3
Bunker station	Space allocated	Space allocated	Bunker lines compatible with both LNG and ammonia (in size and materials)
Tank	LR2: LNG tanks **not** compatible with ammonia; space allocated for the second pair of tanks VLCC: LNG tanks compatible with ammonia	LR2: LNG tanks compatible with ammonia; space allocated for the second pair of tanks VLCC: LNG tanks compatible with ammonia	As level 2
Fuel prep room	LNG fuel prep room dimensioned to accommodate the ammonia supply system, circulation tank, and reliquefication equipment required for ammonia	As level 1	As level 1
Fuel supply system	LNG system to be designed and arranged for easy replacement with ammonia equipment	As level 1	As level 1, plus pipes for ammonia installed
Main engine	Maker and engine bore to be chosen for possible later conversion	As level 1	As level 1
Auxiliary engines and boiler	Maker and model to be chosen for possible later conversion	As level 1	As level 1
Ventilation	Space for ammonia ventilation system allocated	As level 1	Ventilation system to be dimensioned for ammonia emergency ventilation
Safety equipment	Space allocated	As level 1, plus upgrade of water/safety pump capacity	As level 2, plus main piping fitted
Electrical installations	Space allocated (possible extension of switchboard included)	As level 1	Spare breakers and busbars installed Main cable tray fitted
Vent mast	Vent mast to be dimensioned and located according to requirements for ammonia	As level 1	As level 1
General	Trim, stability, and longitudinal strength to be considered for future conversion	As level 1, plus risk analysis to be carried out	As level 2

5.3 Techno-economic analysis of LNG to ammonia conversions

5.3.1 CapEx

Tables 13 and 14 show the estimated CapEx investments for newbuilding and converting each vessel design and preparation level outlined in Sections 5.1 and 5.2. Unlike the conversions from fuel oil to methanol or ammonia, here the CapEx is formulated in terms of percentage of newbuild cost (% NB cost) of an **LNG-fuel oil dual-fuel newbuild**. For comparison, we have also included CapEx figures as a percentage of the cost for a standard fuel oil newbuild.

Table 13: CapEx estimates for conversion of LR2 tanker vessel from LNG to ammonia.

LR2 tanker, LNG-ammonia conversion CapEx (% of LNG DF newbuild) — full range					
	Prep level 0 (% of NB cost)	Prep level 1 (% of NB cost)	Prep level 2 (% of NB cost)	Prep level 3 (% of NB cost)	Prep level 4 (% of NB cost)
Prep cost	0%	0%	3%	4%	n/a
Conversion cost	34%	32%	25%	22%	n/a
Total cost	34%	32%	28%	26%	n/a
CapEx in % of standard FO newbuild to compare with ammonia DF					
Total cost for LNG option + ammonia conversion	62%	60%	56%	53%	27%

⟶

DF = dual fuel, FO = fuel oil, NB = newbuild, n/a = not applicable.

←

LR2 tanker, LNG-ammonia conversion CapEx (% of LNG DF newbuild) — reduced range					
	Prep level 0 (% of NB cost)	Prep level 1 (% of NB cost)	Prep level 2 (% of NB cost)	Prep level 3 (% of NB cost)	Prep level 4 (% of NB cost)
Prep cost	0%	0%	2%	3%	n/a
Conversion cost	32%	31%	25%	22%	n/a
Total cost	32%	31%	27%	25%	n/a
CapEx in % of standard FO newbuild to compare with ammonia DF					
Total cost for LNG option + ammonia conversion	61%	59%	55%	52%	25%

LR2 tanker, LNG-ammonia conversion CapEx (% of LNG DF newbuild) — limited range					
	Prep level 0 (% of NB cost)	Prep level 1 (% of NB cost)	Prep level 2 (% of NB cost)	Prep level 3 (% of NB cost)	Prep level 4 (% of NB cost)
Prep cost	0%	0%	2%	3%	n/a
Conversion cost	28%	26%	20%	18%	n/a
Total cost	28%	26%	22%	21%	n/a
CapEx in % of standard FO newbuild to compare with ammonia DF					
Total cost for LNG option + ammonia conversion	56%	54%	49%	47%	25%

Table 14: CapEx estimates for conversion of VLCC tanker vessel from LNG to ammonia.

VLCC, LNG-ammonia conversion CapEx (% of LNG DF newbuild) — reduced range					
	Prep level 0 (% of NB cost)	Prep level 1 (% of NB cost)	Prep level 2 (% of NB cost)	Prep level 3 (% of NB cost)	Prep level 4 (% of NB cost)
Prep cost	0%	5%	5%	7%	n/a
Conversion cost	28%	14%	13%	10%	n/a
Total cost	28%	19%	18%	17%	n/a
CapEx in % of standard FO newbuild to compare with ammonia DF					
Total cost for LNG option + ammonia conversion	63%	53%	52%	50%	31%

DF = dual fuel, FO = fuel oil, NB = newbuild, n/a = not applicable.

5.3.2 Total cost

In this section, we present estimates of the total cost of LNG-ammonia conversion for our four reference designs. This assessment includes the cost of lost cargo capacity before and after conversion. Results are presented as present value (PV) of the cost depending on time since newbuild.

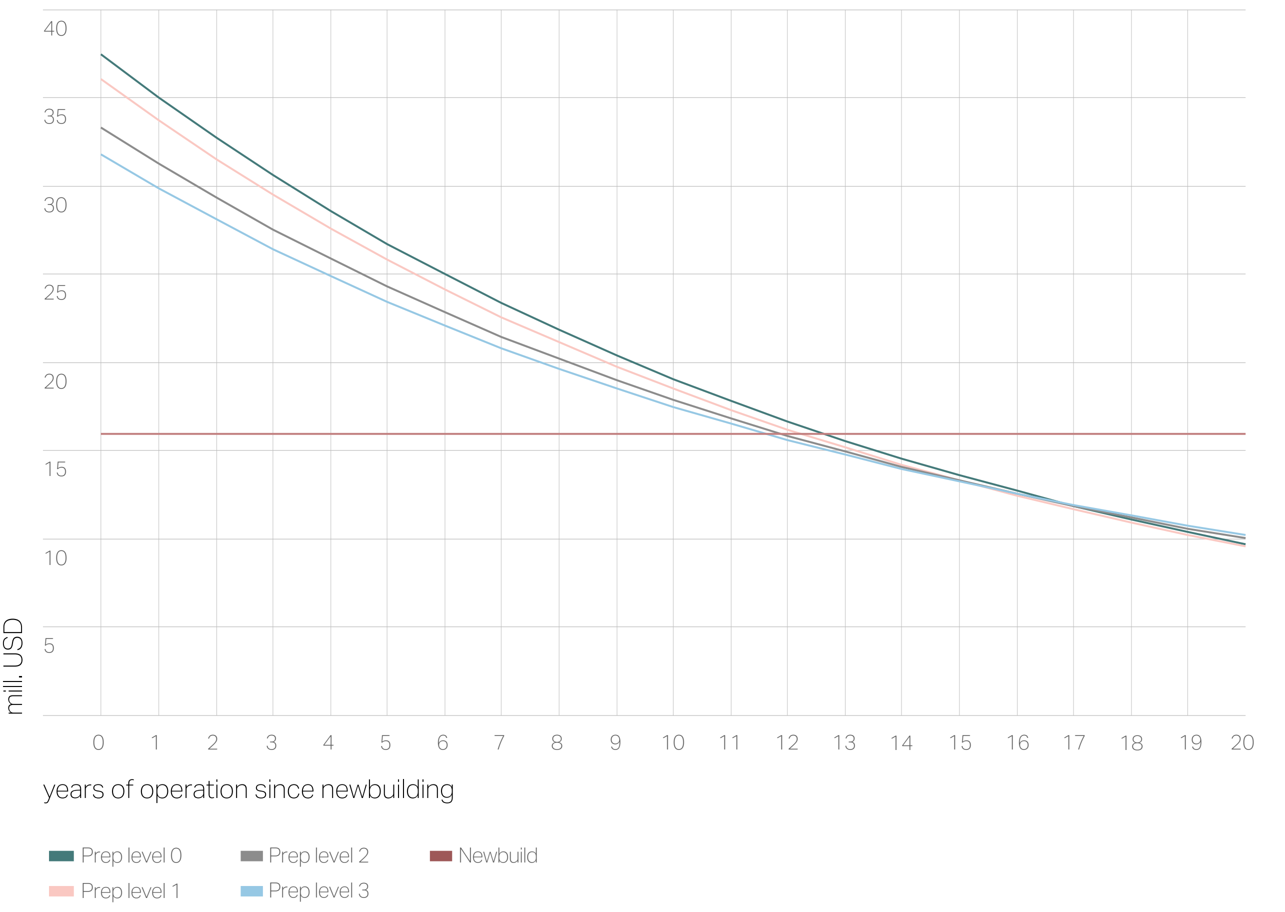
The conversion from LNG to ammonia has a different reference compared to conversions from a standard fuel oil vessel, as additional CapEx has been added to the fuel oil newbuild for the LNG configuration. The total cost of conversion is still compared with an ammonia dual-fuel newbuild. However, we assume that the investment in LNG is based on a business case where LNG is cheaper than FO, and the investment in LNG is being paid back over time. When comparing LNG-ammonia conversions to an ammonia dual-fuel newbuild, the additional CapEx for LNG configuration has been added as a preparation cost, and the fuel cost savings related to LNG are also included in our total cost assessment.

Figure 18 shows the present-value total cost of conversion from LNG to ammonia for a full-range LR2 tanker vessel. The equivalent figures for the other three vessel designs are provided in the Appendix.

As shown in Figure 18, if the full-range LR2 vessel begins operating on ammonia within 12 years, a dual-fuel (ammonia-fuel oil) newbuild (brick red line) is the least expensive option. If operation on ammonia begins 12-16 years after newbuilding, preparation level 3 (blue line) is the least expensive. If operation on ammonia begins after 16-20 years, preparation level 1 (pink line) is the least expensive.

For the reduced-range LR2 design, a dual-fuel (ammonia-fuel oil) newbuild is the least expensive option if operation on ammonia begins within 12 years.

Figure 18: Present value of total LNG-ammonia conversion cost for a full-range LR2 tanker vessel.



If operation on ammonia begins 12-16 years after newbuilding, preparation level 3 is the least expensive. If operation on ammonia begins after 16-20 years, preparation level 1 is the least expensive.

For the limited-range LR2 design, a dual-fuel (ammonia-fuel oil) newbuild is the least expensive option if operation on ammonia is expected within 10.5 years. For conversion to ammonia operation after 10.5-18 years, preparation level 2 is the least expensive option, and for conversion after 18-20 years, preparation level 1 is the least expensive; however, this is not relevant due to vessel age.

The reduced-range VLCC design was again compared to a reduced-range newbuild (see Sections 3.3.2 and 4.3.2). For this design, a reduced-range dual-fuel (ammonia-fuel oil) newbuild is the least expensive option if operation on ammonia begins within 5 years. Preparation level 3 is the least expensive option if ammonia operation begins within 5-11 years, and preparation level 1 or 2 is cheapest if ammonia operation begins after 11-15 years.

Table 15 summarizes our recommendations for tanker newbuild preparation levels based on these analyses of total cost. As for the fuel oil to methanol and ammonia cases, shipowners should carefully consider their individual circumstances when planning vessels and conversions.

Table 15: Recommendations for tanker vessel preparation levels for conversion from LNG to ammonia based on present-value total cost and time since newbuild.

LR2 tanker, LNG-ammonia, full range conversion			
Years of operation since newbuild	0-12 years	12-16 years	16-20 years
Lowest PV cost option	DF ammonia newbuild	Prep level 3	Prep level 1
LR2 tanker, LNG-ammonia, reduced range conversion			
Years of operation since newbuild	0-12 years	12-16 years	16-20 years
Lowest PV cost option	DF ammonia newbuild	Prep level 3	Prep level 1
LR2, LNG-ammonia, limited range conversion			
Years of operation since newbuild	0-10.5 years	10.5-18 years	18-20 years
Lowest PV cost option	DF ammonia newbuild	Prep level 2	Prep level 1
VLCC, LNG-ammonia, reduced range conversion			
Years of operation since newbuild	0-5 years	5-11 years	11-15 years
Lowest PV cost option	DF ammonia newbuild	Prep level 3	Prep level 1/2

DF = dual fuel, PV = present value.

5.3.3 Sensitivity analysis

As with the fuel oil-methanol and fuel oil-ammonia conversions, we carried out a sensitivity analysis to better understand the impacts of cargo loss value and off-hire costs on our results.

As in the previous conversion cases, the impact of cargo loss value is only relevant to the VLCC. We found that if the cargo value is doubled, the impact on the period for which a given preparation level is recommended is not visible.

Regarding the impact of off-hire costs, every 0.5 million USD in off-hire costs added to cost of conversion generally increases the break-even point between a dual-fuel newbuild and a conversion-ready newbuild by 0.1 years for both the LR2 and VLCC. Therefore, if a dual-fuel newbuild is nominally the cheapest option for the first 5 years, but 0.5 million USD in off-hire costs is added, this period increases to 5.1 years for both vessel types.

06 GHG emissions assessment

For all fuel conversion options, we also studied the impact of conversion on lifetime operational GHG emissions. We considered carbon dioxide (CO_2) emissions for all conversion options, as well as methane emissions (as CO_2 equivalent) in the case of LNG to ammonia conversions.

Specifically, we compared the estimated operational GHG emissions for a reference vessel using fuel oil for its entire operational lifetime to an equivalent vessel converted to operation on either methanol or ammonia after five or ten years of operation. For the LNG to ammonia conversion case, we included estimated GHG emissions from lifetime operation on both fuel oil and LNG in the comparison. However, the emissions until conversion are based on operation on LNG.

As combustion of green methanol and ammonia does not produce fossil CO_2 or methane slip, any emissions after conversion relate to the pilot fuel required for the main and auxiliary engines. We have assumed that this pilot fuel will be fossil-based, but if a CO_2-neutral pilot fuel is used, these emissions can be considered as zero. Representative estimates of CO_2 emissions from building, conversion, and scrapping are also included for comparison. We have not included any potential N_2O emissions from ammonia combustion, as this level is not yet known and is assumed to be dealt with by after-treatment if needed.

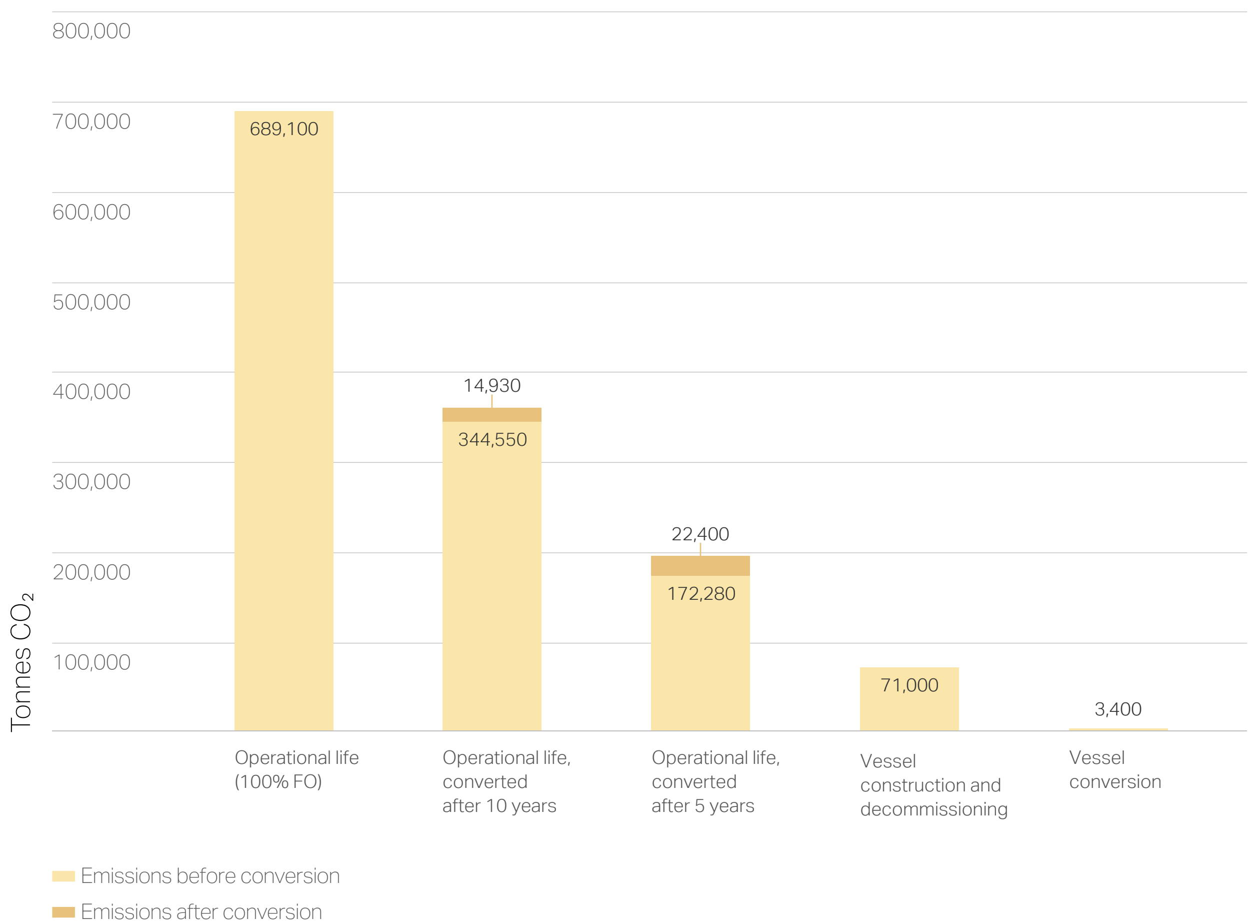
For both the LR2 and VLCC designs, it is clear that conversion to methanol or ammonia even after ten years of operation on fuel oil or LNG can considerably reduce lifetime GHG emissions, and that the emissions impact of conversion is minimal compared to the operational emissions. However, it is important to also carefully assess the economic or business applicability of making a conversion so late in an asset's lifetime.

6.1 Fuel oil to methanol conversion

We compared the estimated operational GHG emissions (in this case, CO_2) for a reference vessel using fuel oil for its entire operational lifetime to an equivalent vessel converted to operation on methanol after five or ten years of operation. The results for an LR2 tanker are shown in Figure 19 and the results for a VLCC tanker in Figure 20.

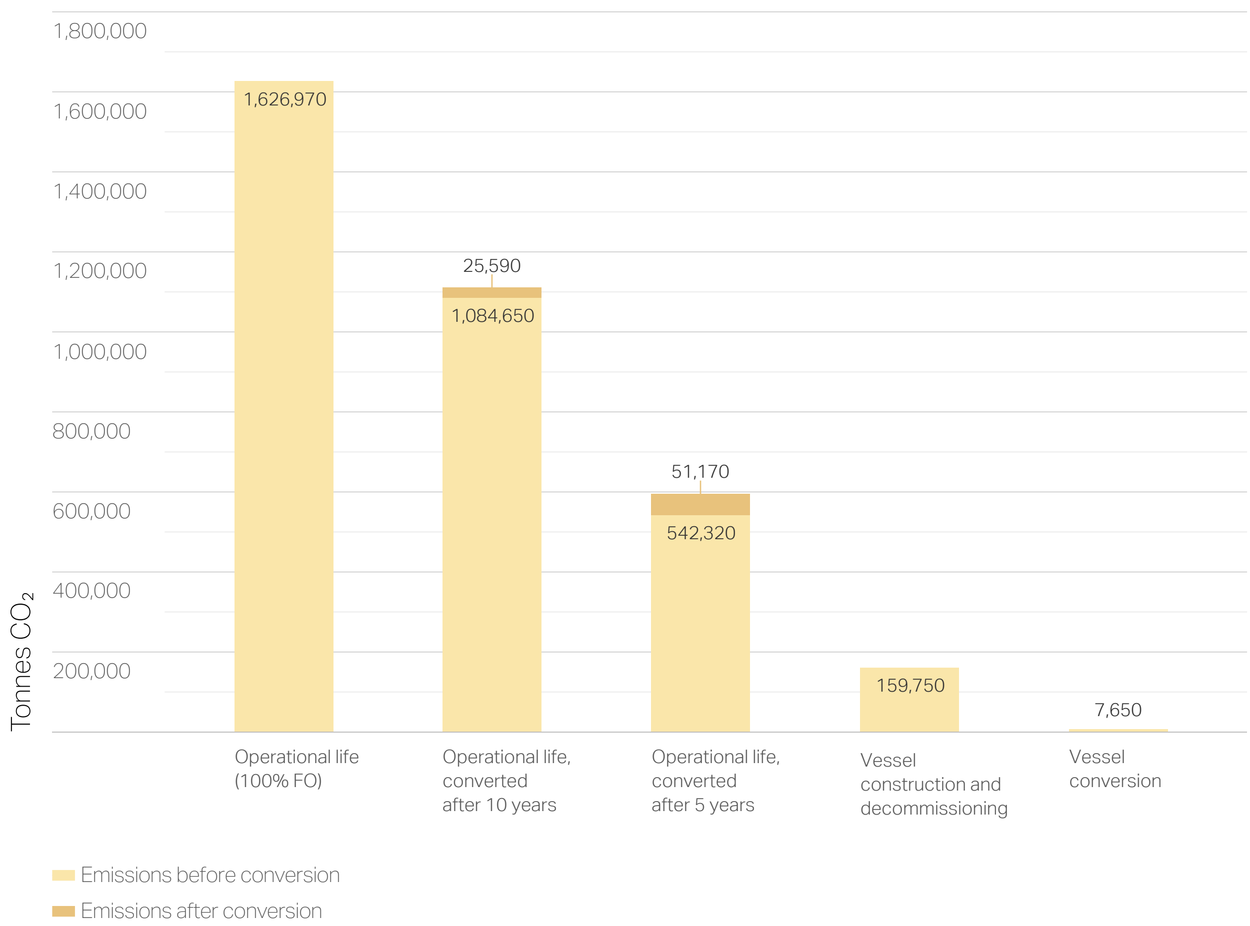
For the LR2 design, the CO_2 emissions from conversion are minimal, equivalent to 0.5% of the lifetime operational emissions using fuel oil. The emissions related to building a new vessel are equivalent to about two years' worth of emissions from operation on fuel oil.

Figure 19: Estimated lifetime operational CO_2 emissions for an LR2 tanker vessel operating on fuel oil or converted to e-methanol operation after five or ten years. Values are rounded to the nearest ten.



For the VLCC design, the CO_2 emissions from conversion are minimal, equivalent to 0.5% of the lifetime operational emissions using fuel oil. The emissions related to building a new vessel are equivalent to about 1.5 years' worth of emissions from operation on fuel oil.

Figure 20: Estimated lifetime operational CO_2 emissions for a VLCC tanker vessel operating on fuel oil or converted to methanol operation after five or ten years. Values are rounded to the nearest ten.

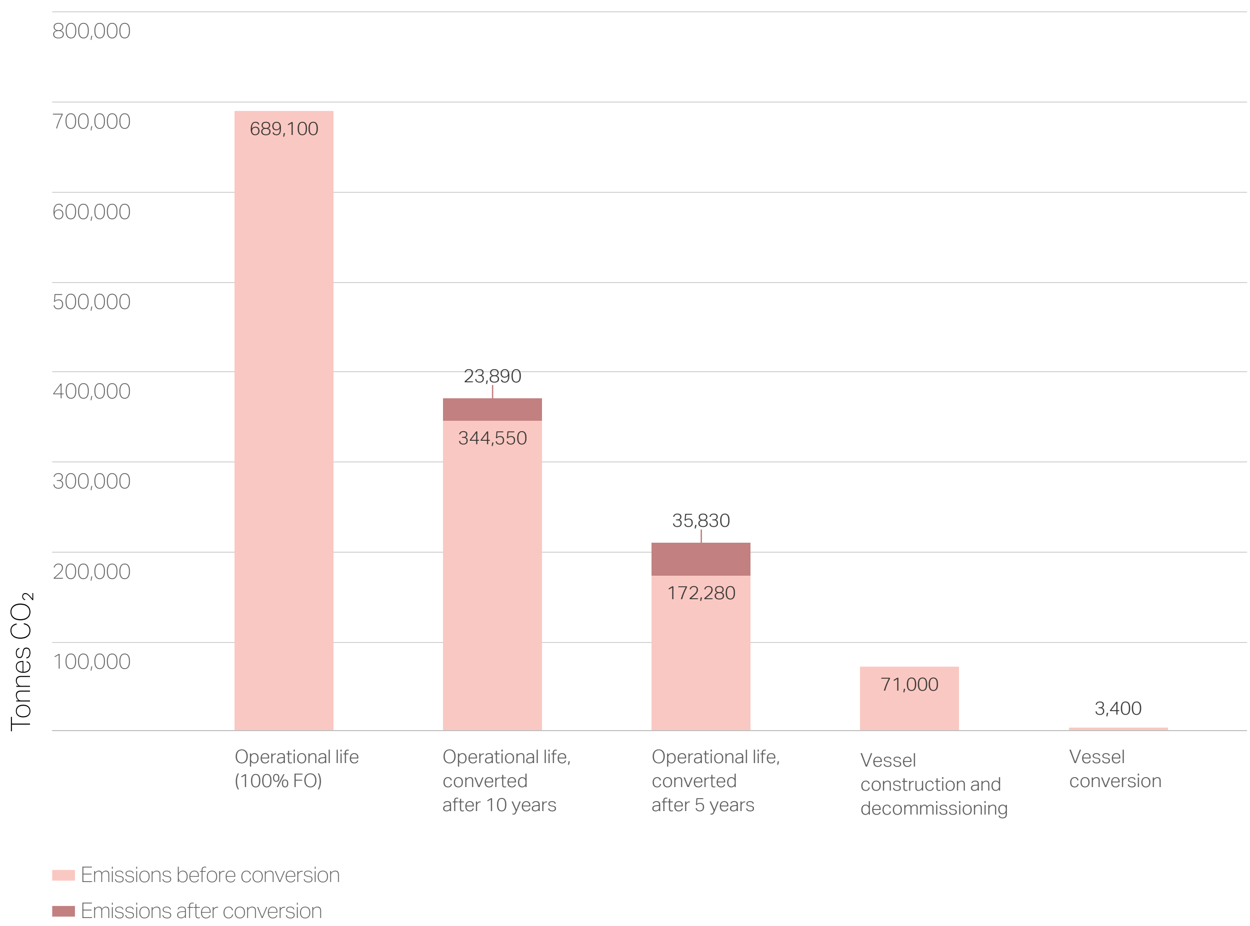


6.2 Fuel oil to ammonia conversion

We compared the estimated operational GHG emissions (in this case, CO_2) for a reference vessel using fuel oil for its entire operational lifetime to an equivalent vessel converted to operation on ammonia after five or ten years of operation. The results for an LR2 tanker are shown in Figure 21 and the results for a VLCC tanker in Figure 22.

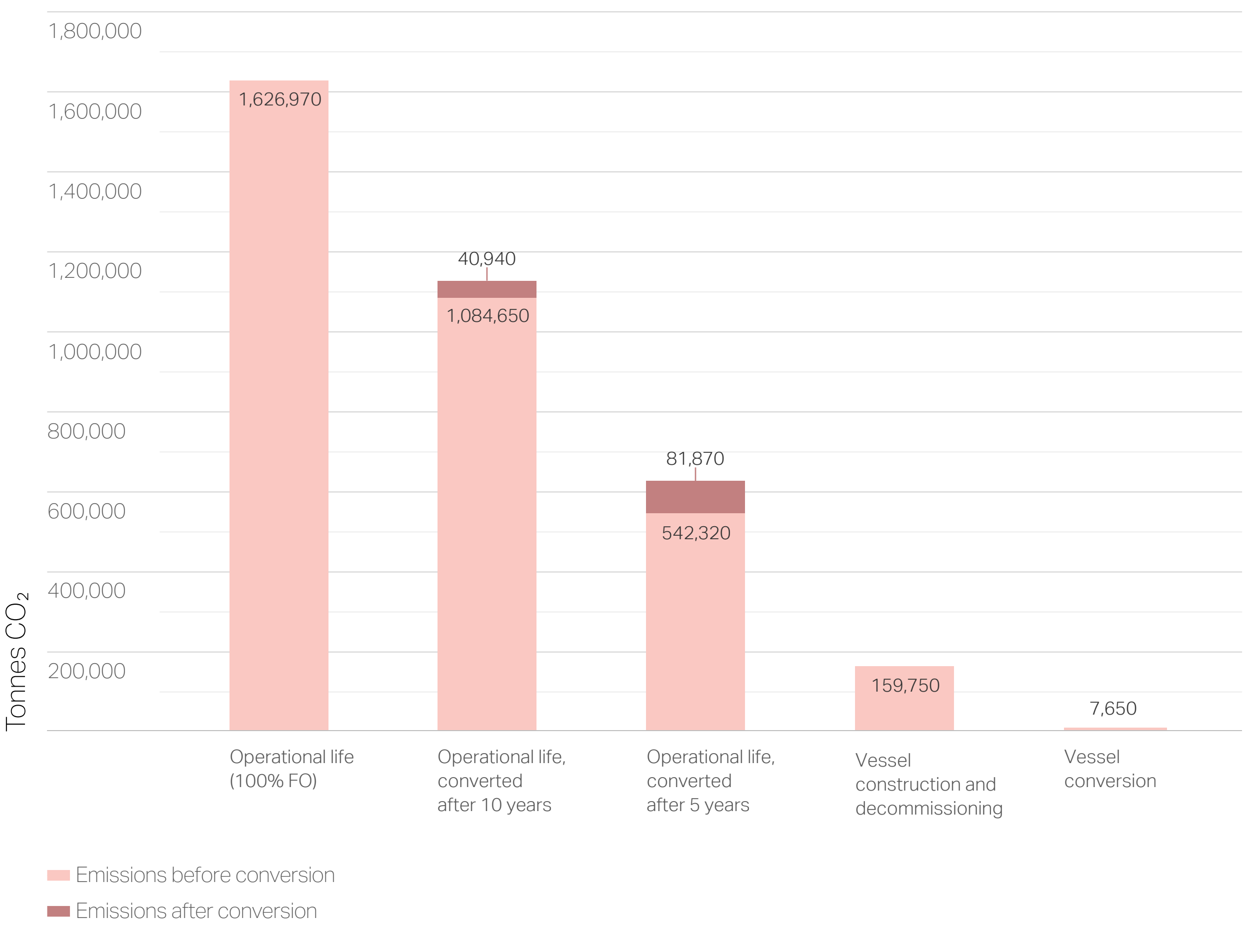
For the LR2 design, the CO_2 emissions from conversion are minimal, equivalent to 0.5% of the lifetime operational emissions using fuel oil. The emissions related to building a new vessel are equivalent to about two years' worth of emissions from operation on fuel oil.

Figure 21: Estimated lifetime operational CO_2 emissions for an LR2 tanker vessel operating on fuel oil or converted to e-ammonia operation after five or ten years. Values are rounded to the nearest ten.



For the VLCC design, the CO_2 emissions from conversion are minimal, equivalent to 0.5% of the lifetime operational emissions using fuel oil. The emissions related to building a new vessel are equivalent to about 1.5 years' worth of emissions from operation on fuel oil.

Figure 22: Estimated lifetime operational CO_2 emissions for a VLCC tanker vessel operating on fuel oil or converted to ammonia operation after five or ten years. Values are rounded to the nearest ten.

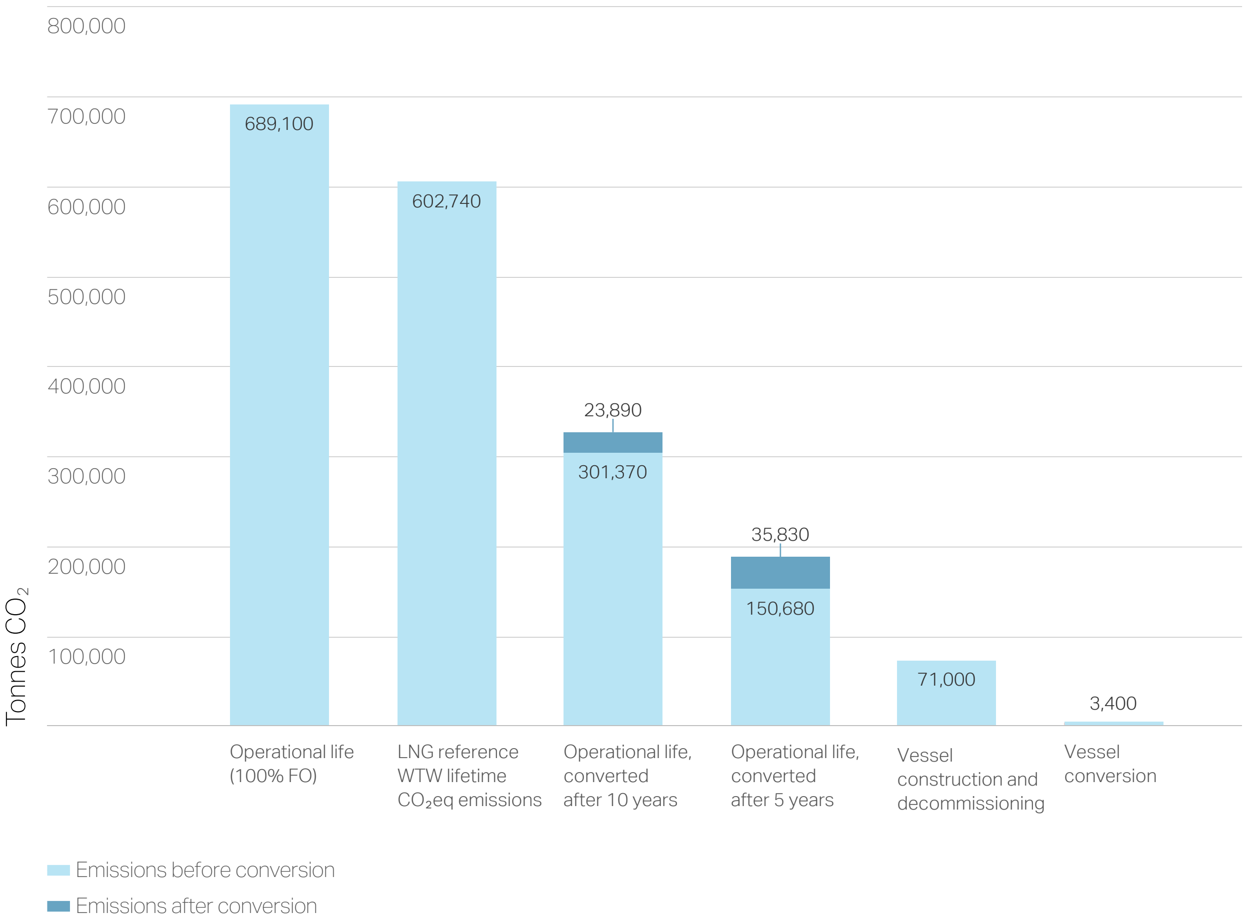


6.3 LNG to ammonia conversion

Finally, we compared the estimated operational GHG emissions (in this case, CO_2 and methane) for a reference vessel using fuel oil for its entire operational lifetime to equivalent vessels with either lifetime operation on LNG or converted to operation on ammonia after five or ten years of operation on LNG. Methane emissions have been converted to CO_2-equivalent values based on a 100-year global warming potential. The results for an LR2 tanker are shown in Figure 23 and the results for a VLCC tanker in Figure 24.

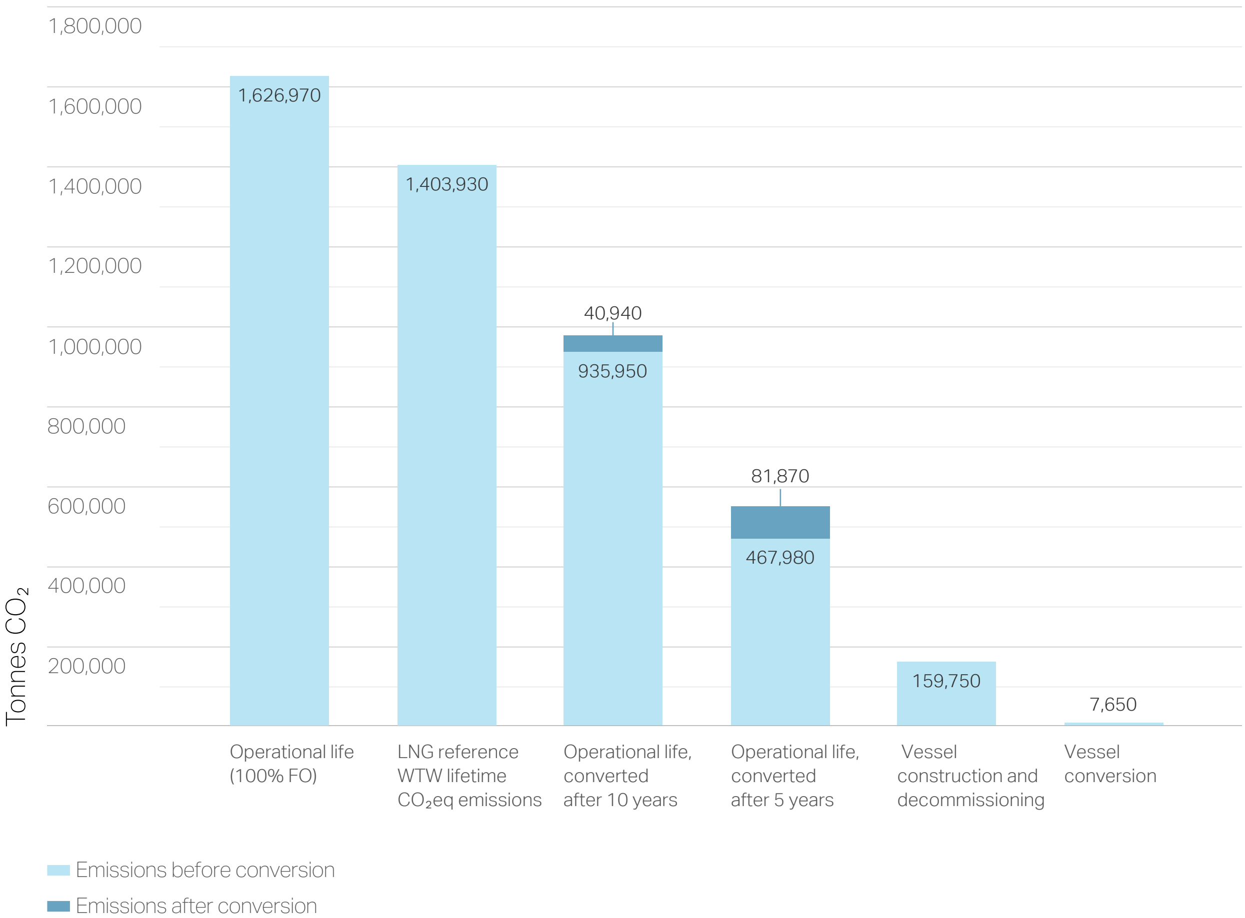
For the LR2 design, using LNG instead of fuel oil results in about 12.5% lower operational GHG emissions over the vessel's operational lifetime. The emissions from conversion to ammonia operation are minimal, equivalent to 0.5% of the lifetime operational emissions using fuel oil or 0.6% of lifetime operational emissions using LNG. The emissions related to building a new vessel are equivalent to about two years' worth of emissions from operation on fuel oil or 2.4 years on LNG.

Figure 23: Estimated lifetime operational CO_2 and methane emissions for an LR2 tanker vessel operating on fuel oil, operating on LNG, or converted to e-ammonia operation after five or ten years. Values are rounded to the nearest ten.



For the VLCC design, using LNG instead of fuel oil results in about 14% lower operational GHG emissions over the vessel's operational lifetime. The emissions from conversion to ammonia operation are minimal, equivalent to 0.5% of the lifetime operational emissions using either fuel oil or LNG. The emissions related to building a new vessel are equivalent to about 1.5 years' worth of emissions from operation on fuel oil or 1.7 years on LNG.

Figure 24: Estimated lifetime operational CO_2 and methane emissions for a VLCC tanker vessel operating on fuel oil, operating on LNG, or converted to ammonia operation after five or ten years. Values are rounded to the nearest ten.



07 Conclusions

In summary, the work presented here shows that upfront investment to prepare for the transition to alternative maritime fuels can pay off. With intelligent ship design and careful planning of conversion timelines, shipowners can optimize their financial outlay while achieving large reductions in vessels' lifetime operational GHG emissions.

We undertook a techno-economic analysis of the costs of building dual-fuel or conversion-ready tanker vessels for future operation on methanol or ammonia. For this analysis, we used designs for two different types of tanker vessel: an LR2 and a VLCC. These vessel types are large and typically travel on long sea routes, meaning that they are highly exposed to the effects of fuel costs and offer potential for high-impact GHG emissions reductions.

The fuel conversion options we considered were fuel oil to methanol, fuel oil to ammonia, and LNG to ammonia. Because methanol and ammonia are less energy-dense than fuel oil or LNG to some extent, considerably more fuel storage space is needed to maintain the same range when operating on these alternative fuels. To minimize lost cargo capacity, we have located the fuel storage tanks on the deck wherever possible in our designs. However, in many cases, a vessel with reduced sailing range on alternative fuels appears to be more commercially feasible than maintaining the full range after conversion.

For the LR2 design, our results indicate that building a conversion-ready or dual-fuel vessel typically increases newbuild CapEx by 14-27% of the cost of a standard fuel oil newbuild, depending on the planned alternative fuel, desired range, and preparation level. The methanol or ammonia fuel tanks can be located on the deck, meaning that little cargo capacity is lost regardless of range or fuel. The total add-on newbuild cost and conversion cost for methanol and ammonia newbuilding and conversions ranges from 14% to 42% of the cost of a standard fuel oil newbuild if converting from fuel oil, or 21-34% of the cost of an LNG newbuild if converting from LNG (Table 16).

Table 16: Cost summary for newbuild or conversion of an LR2 tanker vessel to dual-fuel capability (fuel oil-methanol, fuel oil-ammonia, or LNG-ammonia).

LR2	Methanol or ammonia DF newbuild cost (Reduced - full range)	Full-range total conversion cost (preparation level 3-0)	Reduced-range total conversion cost (preparation level 3-0)	Limited-range total conversion cost (preparation level 3-0)
Fuel oil to methanol (% of fuel oil newbuild cost)	14-15%	~20-30% (23%-27%)	~20-30% (22-26%)	n/a
Fuel oil to ammonia (% of fuel oil newbuild cost)	25-27%	~35-45% (37-42%)	~35-45% (35-41%)	n/a
LNG to ammonia (% of LNG newbuild cost)	n/a	~25-35% (26-34%)	~25-35% (25-32%)	~20-30% (21-28%)
LNG to ammonia (% of fuel oil newbuild cost)	n/a	~55-65% (53-62%)	~55-65% (52-61%)	~50-60% 47-56%

DF = dual-fuel.

If operation on the alternative fuel is expected on shorter timelines (5-7.5 years when converting from fuel oil, depending on the desired fuel and range), a dual-fuel newbuild that is ready to use the alternative fuel makes the most economic sense. If converting from LNG to ammonia, 10.5-12 years of operation is needed before total cost of conversion is lower than that of building an ammonia dual-fuel newbuild. For longer conversion timelines, the vessel can be built at different levels of preparation for alternative fuels. Our results suggest that the choice of preparation level can impact newbuild CapEx by about 1-3% of the fuel oil newbuild cost, or up to about 4% of LNG newbuild cost in the case of LNG to ammonia conversions. The relatively high preparation cost for LNG to ammonia is mainly due to the need for stainless steel tanks and pipe systems prepared for ammonia.

For the VLCC design, we found that building a conversion-ready or dual-fuel vessel increases newbuild CapEx by 1-36% of the cost of a standard fuel oil newbuild. To maintain full range when operating on methanol or ammonia, this design requires additional fuel tanks located in the cargo storage area, which makes the vessel commercially unviable in the current market. If a reduced range is acceptable, the vessel's methanol or ammonia storage needs can be met using fuel tanks located on the deck. The total add-on newbuild cost and conversion cost for newbuilding and conversions ranges from 17% to 54% of the cost of a standard fuel oil newbuild if converting from fuel oil, or 17-28% of the cost of an LNG newbuild (Table 17).

Due to the required loss of cargo capacity, full-range operation on alternative fuels is generally not viable for the VLCC. For the sake of comparison, a full-range dual-fuel newbuild is only the most cost-effective option if operation on methanol or ammonia begins within 1.5 years after newbuilding. For a reduced-range vessel, a dual-fuel newbuild is most attractive if operation on methanol or ammonia begins within 4-6 years, depending on the fuel. For a newbuild being prepared for later conversion to an alternative fuel, our results suggest that the choice of preparation level can impact cost by about 1-6% of the fuel oil newbuild cost, or 5-7% of the cost of an LNG newbuild if converting from LNG. Similar to the LR2, the relatively high preparation cost for the LNG-fueled vessel is due to tank and system preparation that is not done for the preparation for methanol and ammonia, where the tanks are installed during conversion.

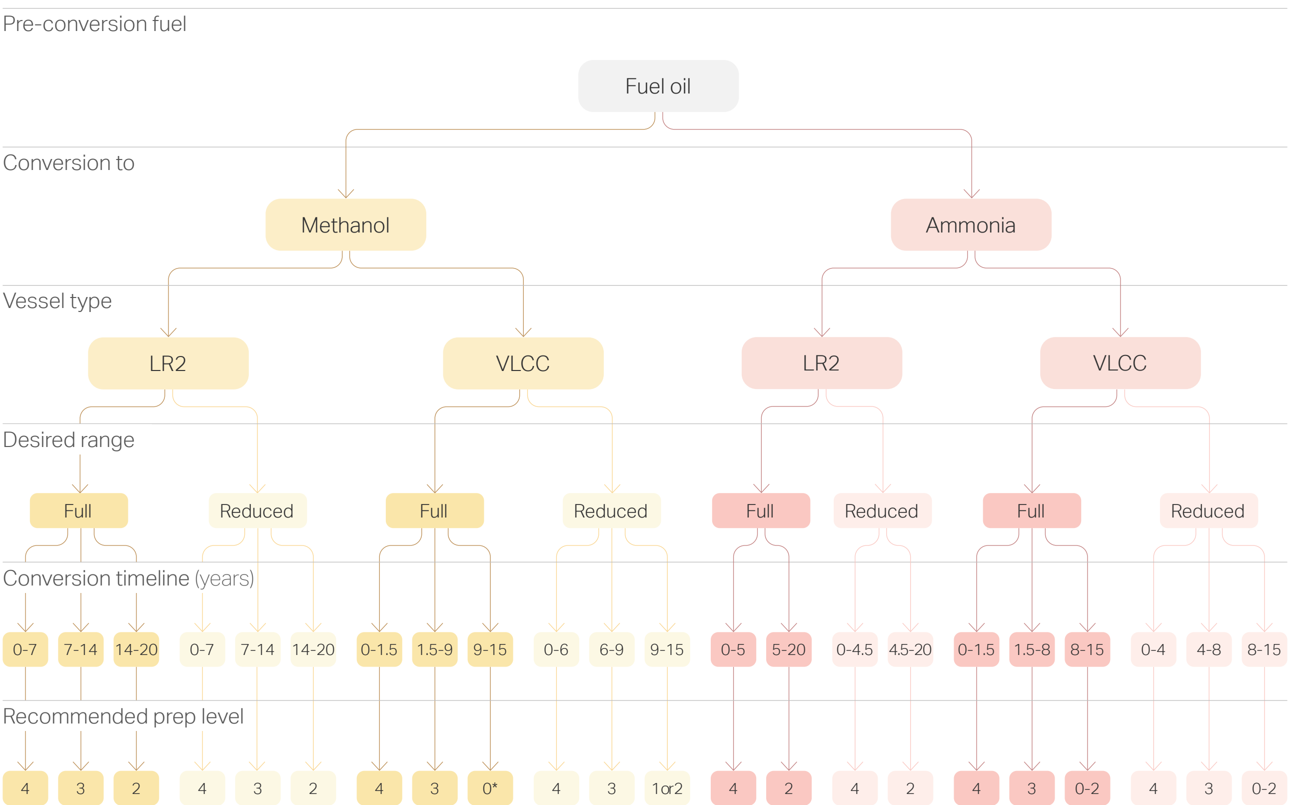
Table 17: Cost summary for newbuild or conversion of a VLCC tanker vessel to dual-fuel capability (fuel oil-methanol, fuel oil-ammonia, or LNG-ammonia).

VLCC	Methanol or ammonia DF newbuild cost (Reduced — full range)	Full-range total conversion cost (preparation level 3-0)	Reduced-range total conversion cost (preparation level 3-0)
Fuel oil to methanol (% of fuel oil newbuild cost)	17-21%	~30-35% (30-34%)	~25-30% (24-29%)
Fuel oil to ammonia (% of fuel oil newbuild cost)	31-36%	~45-55% (46-54%)	~40-45% (39-45%)
LNG to ammonia (% of LNG newbuild cost)	n/a	Not relevant	~20-30% (17-28%)
LNG to ammonia (% of fuel oil newbuild cost)	n/a	Not relevant	~50-65% (50-63%)

DF = dual-fuel.

Based on these findings, we offer some representative recommendations for alternative fuel preparation levels at the newbuilding phase, which are summarized in Figures 25 and 26. The most cost-effective option varies based on choice of vessel type, fuel, range, and conversion timeline. Furthermore, while we chose to limit this study to a small number of fuel conversion pathways (see Section 2), this does not necessarily mean that other pathways should be discounted. Therefore, shipowners need to carefully consider which options are realistic for their situation and plan accordingly. For example, our results indicate that LNG to ammonia conversions are a comparatively CapEx-intensive route to green fuel capability: therefore, owners of dual-fuel LNG vessels could also consider sustainable bio- or e-methane in their green fuel strategies.

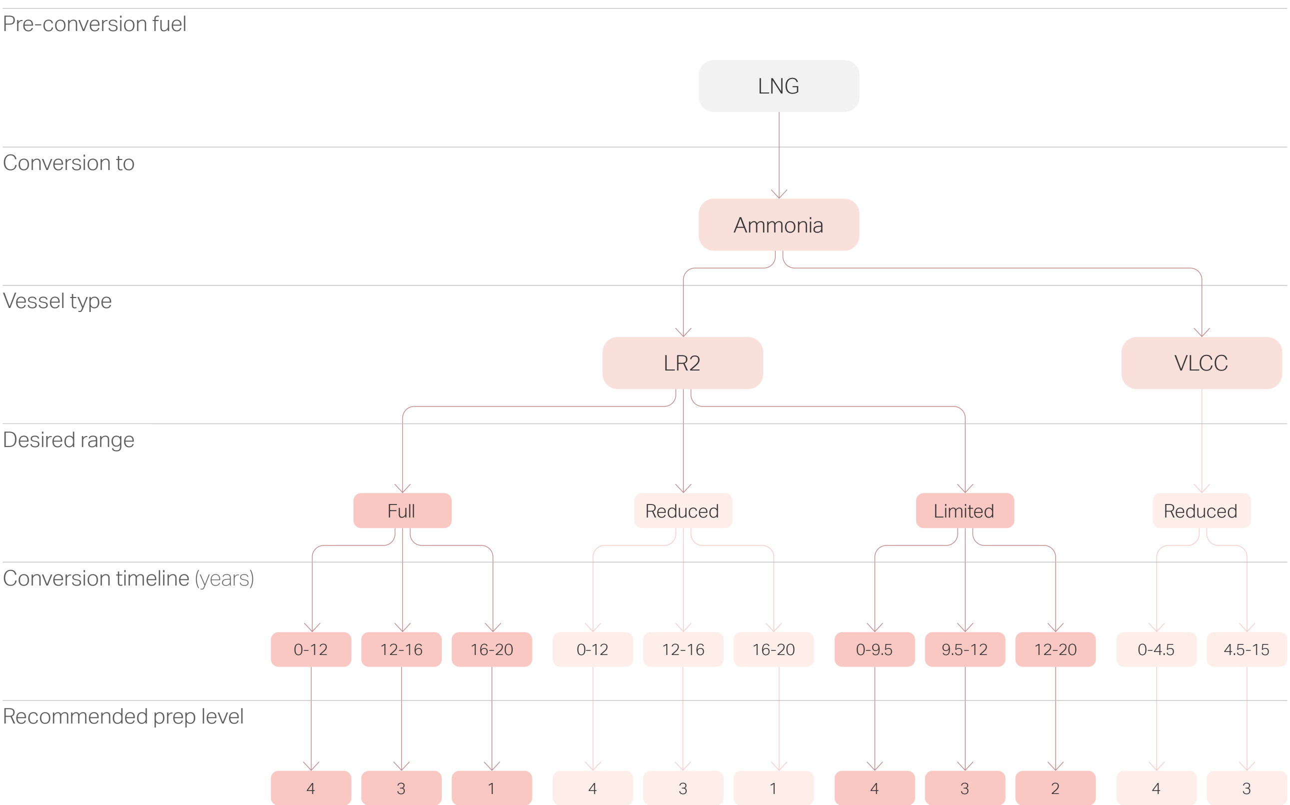
Figure 25: Recommended preparation levels for conversion from fuel oil to methanol or ammonia based on conversion timelines and desired range.



*not commercially viable

Our analysis also indicates that significant reductions in lifetime operational GHG emissions can be achieved by transitioning tanker vessels from operation on fuel oil or LNG to methanol or ammonia. This is true even if the vessels first operate on conventional fuels for five to ten years before transitioning to alternative fuels, considering at the same time the financial viability of such a decision. The CO_2 emissions generated by the work of converting an existing vessel from a conventional to an alternative fuel system are minimal — equivalent to 0.5% of lifetime emissions from operating on fuel oil. The emissions related to building a new vessel are equivalent to operational CO_2 emissions from 1.5-2 years of operation on fuel oil or 1.7-2.4 years on LNG, depending on the vessel type. Therefore, preparing tankers for transition to alternative fuels can create meaningful climate benefits.

Figure 26: Recommended preparation levels for conversion from LNG to ammonia based on conversion timelines and desired range.



08 The project team

This report was prepared by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) with assistance from our partners. Team members marked with an asterisk (*) were seconded to the MMMCZCS from their home organizations. Affiliations are current as of this report going to press.

Lead author: Claus Rud Hansen* (Maersk).

Contributing authors and project participants:
Jun Kato (NYK Line), Jun Ito* (NYK Line), Koichi Matsushita* (MHI), Koichi Sato* (MHI), Takashi Unseki (MHI), Daisuke Yamada (MHI), Viviane Philippe (TotalEnergies), Robert Bridges* (TotalEnergies), Rene Laursen (ABS), Jan Otto de Kat (MMMCZCS), Inoue Tadashi (Tsuneishi Shipbuilding), Miu Hatamura (Tsuneishi Shipbuilding), Benjamin Attumaly (MAN), Peter Nerenst (MAN), Thomas McKenney (University of Michigan).

Steering committee: Claus Graugaard (MMMCZCS), Sebastien Roche (TotalEnergies), Tomoo Kuzu (MHI), Satoshi Sueno (MHI), Jun Kato (NYK Line).

Reviewers: Robert Bridges* (TotalEnergies), Jun Ito* (NYK Line).

Editor: Matilda Handsley-Davis (MMMCZCS).

Design: SPRING Production.

Abbreviations

ABS	American Bureau of Shipping
CapEx	Capital expenditure
CO_2	Carbon dioxide
DWT	Deadweight tonnage
FPR	Fuel preparation room
GHG	Greenhouse gas
IMO	International Maritime Organization
LNG	Liquefied natural gas
LOA	Overall length
LPG	Liquefied petroleum gas
LR2	Long-range 2
m^3	Cubic meter(s)
MHI	Mitsubishi Heavy Industries
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
NM	Nautical miles
PG-FE	Persian Gulf-Far East Asia [trade route]
PV	Present value
VLCC	Very large crude (oil) carrier

Appendix: Additional estimates of present-value total costs of fuel conversions

This appendix contains additional figures depicting our analysis of present-value total costs of vessel fuel conversions. The key results from each graph are discussed in the relevant section of the main document (Section 3.3.2 for fuel oil-methanol conversions, Section 4.4.2 for fuel oil-ammonia conversions, Section 5.4.2 for LNG-ammonia conversions).

Fuel oil to methanol conversions

Figure 27: Present value of total fuel oil-methanol conversion cost for a reduced-range LR2 tanker vessel.

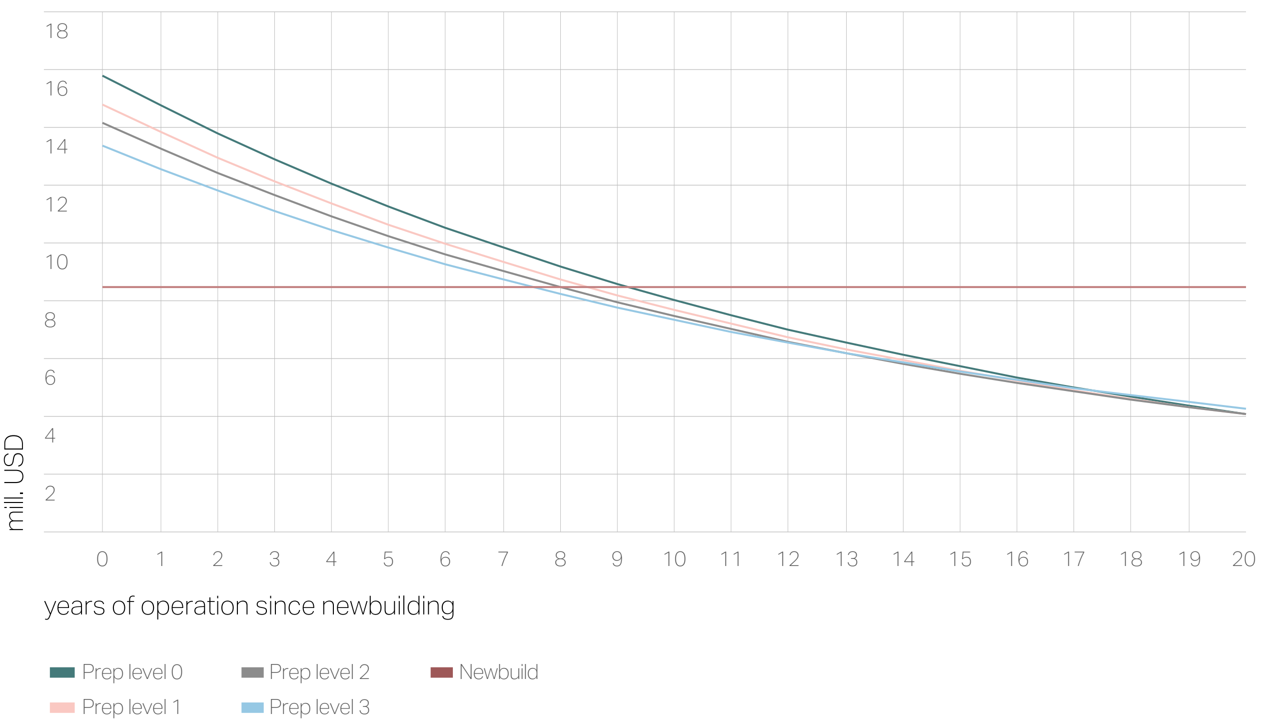


Figure 28: Present value of total fuel oil-methanol conversion cost for a full-range VLCC tanker vessel.

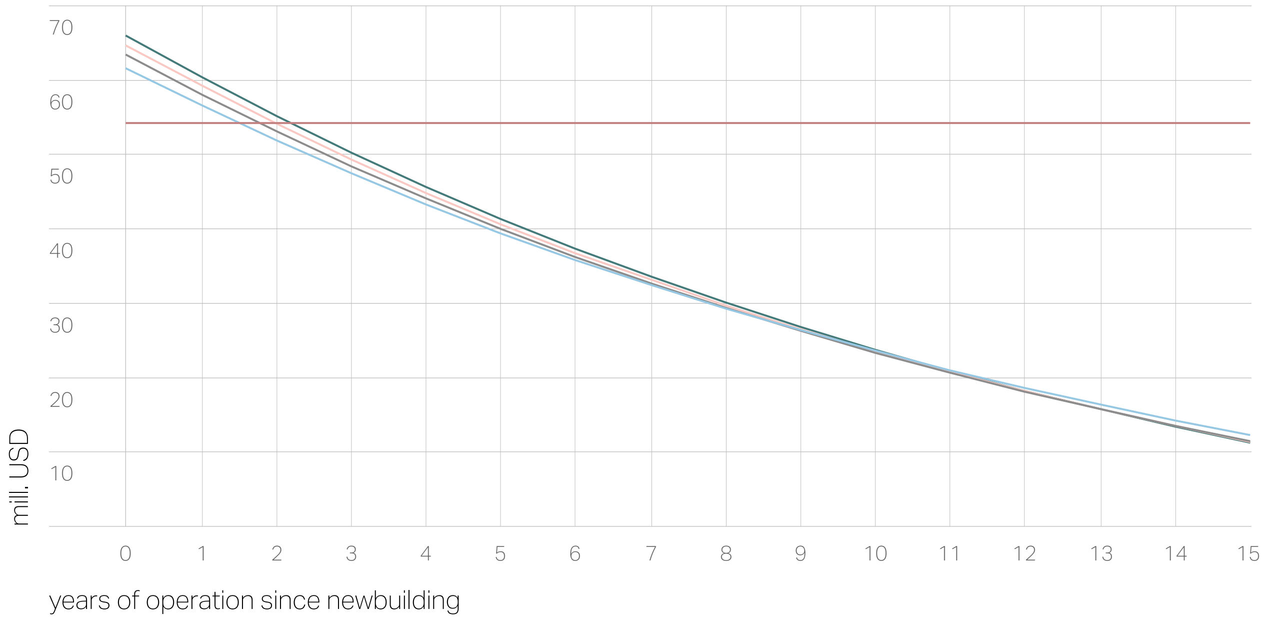
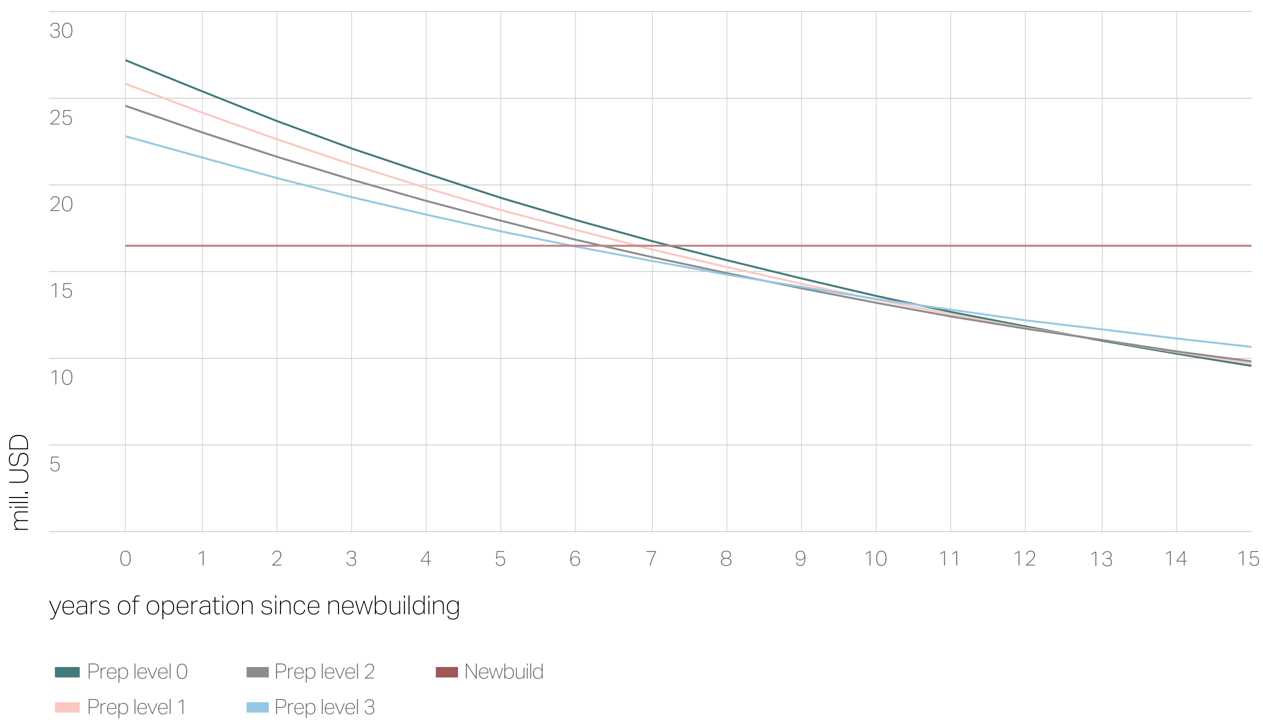


Figure 29: Present value of total fuel oil-methanol conversion cost for a reduced-range VLCC tanker vessel.



Fuel oil to ammonia conversions

Figure 30: Present value of total fuel oil-ammonia conversion cost for a reduced-range LR2 tanker vessel.

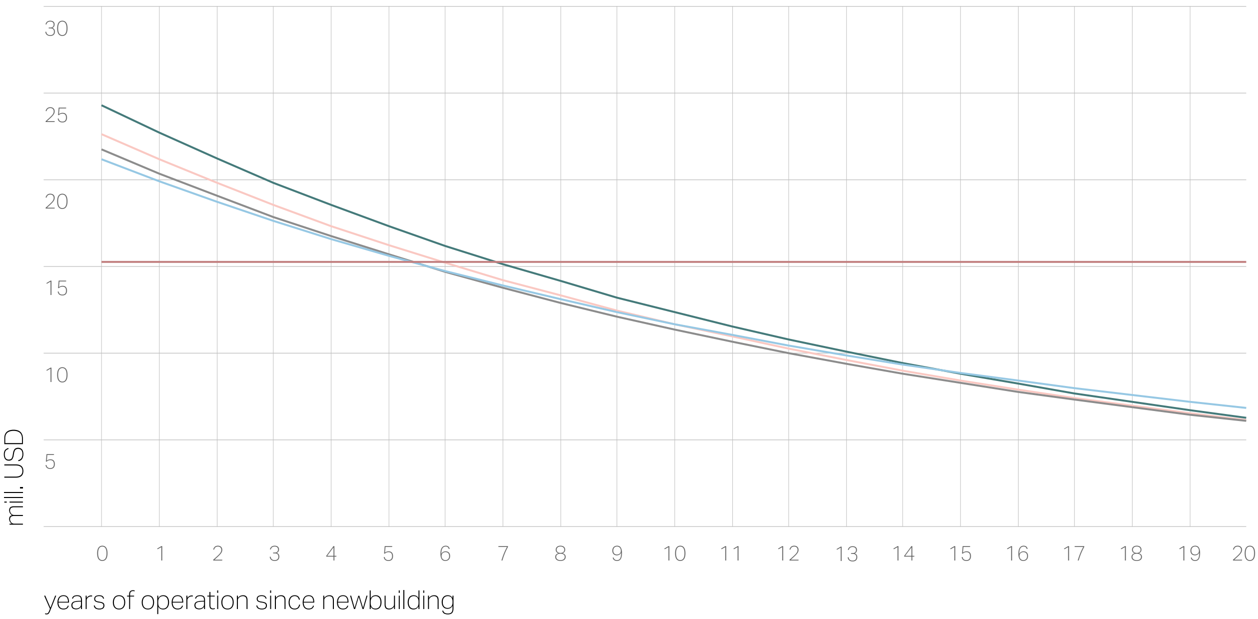


Figure 31: Present value of total fuel oil-ammonia conversion cost for a full-range VLCC tanker vessel.

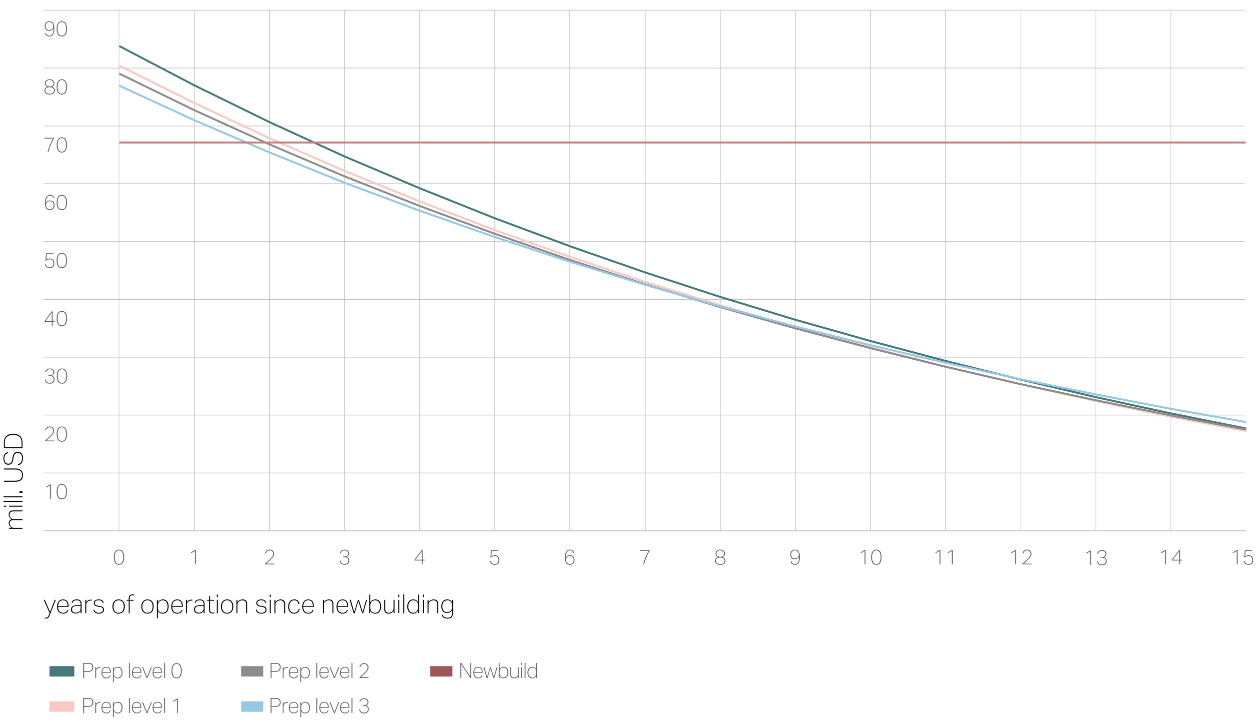
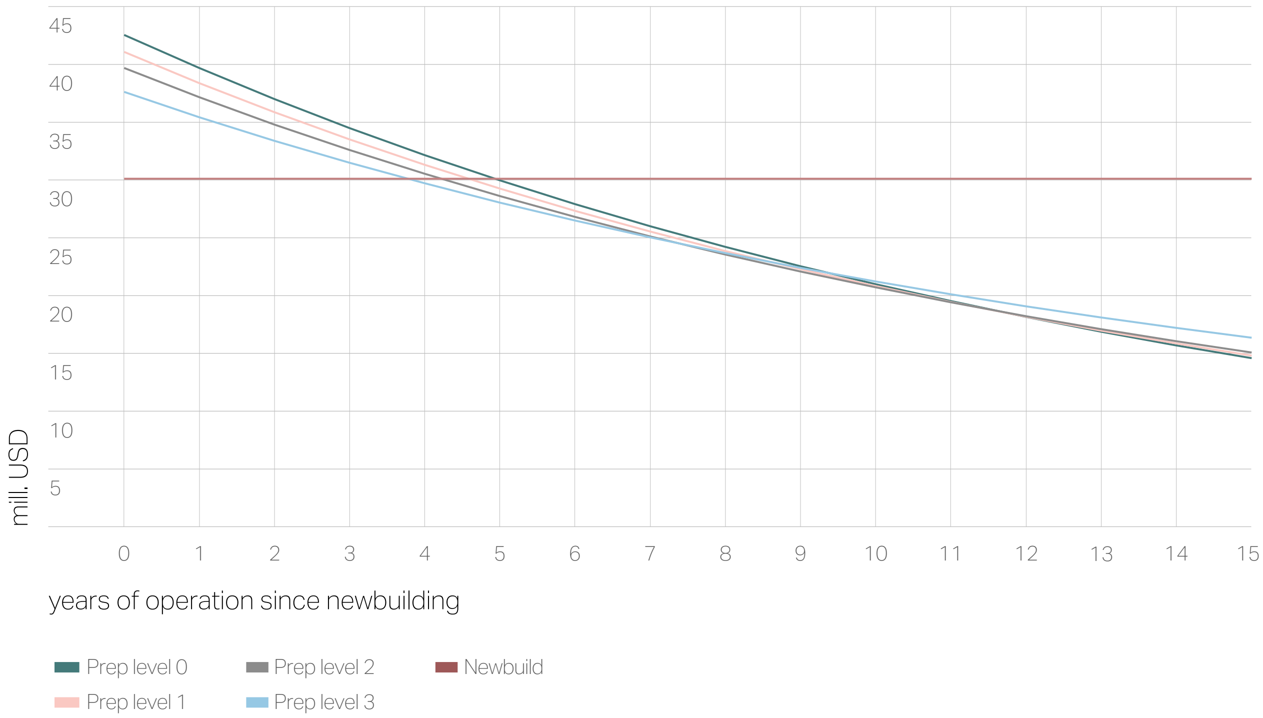


Figure 32: Present value of total fuel oil-ammonia conversion cost for a reduced-range VLCC tanker vessel.



LNG to ammonia conversions

Figure 33: Present value of total LNG-ammonia conversion cost for a reduced-range LR2 tanker vessel.

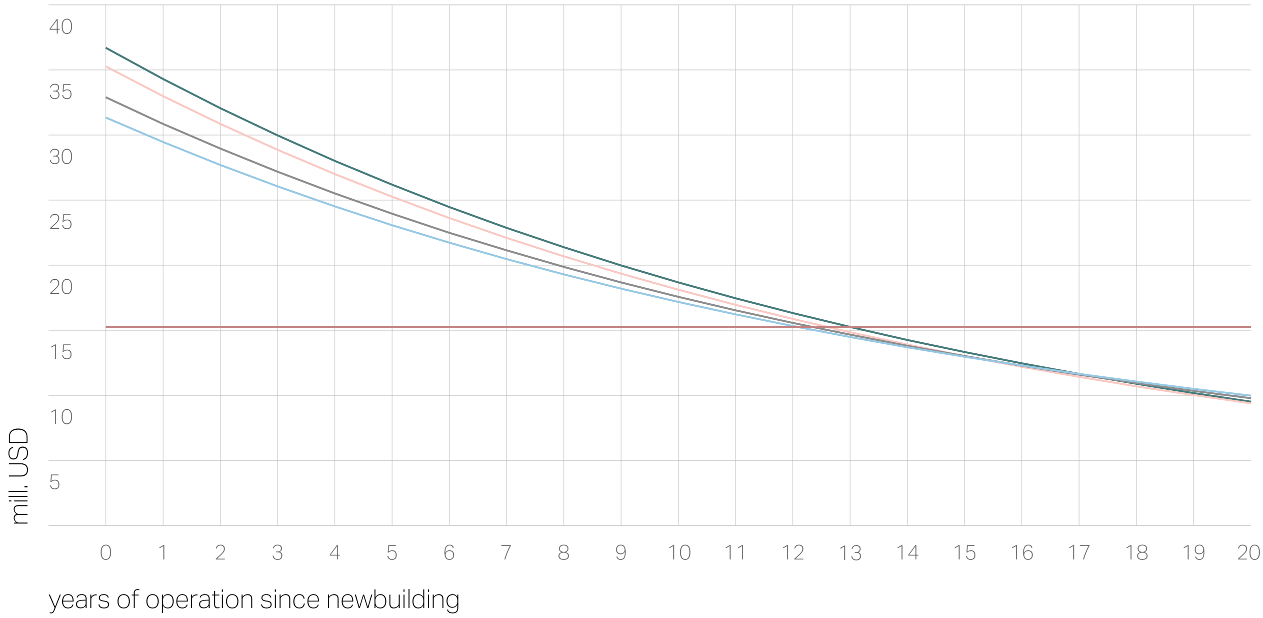


Figure 34: Present value of total LNG-ammonia conversion cost for a limited-range LR2 tanker vessel.

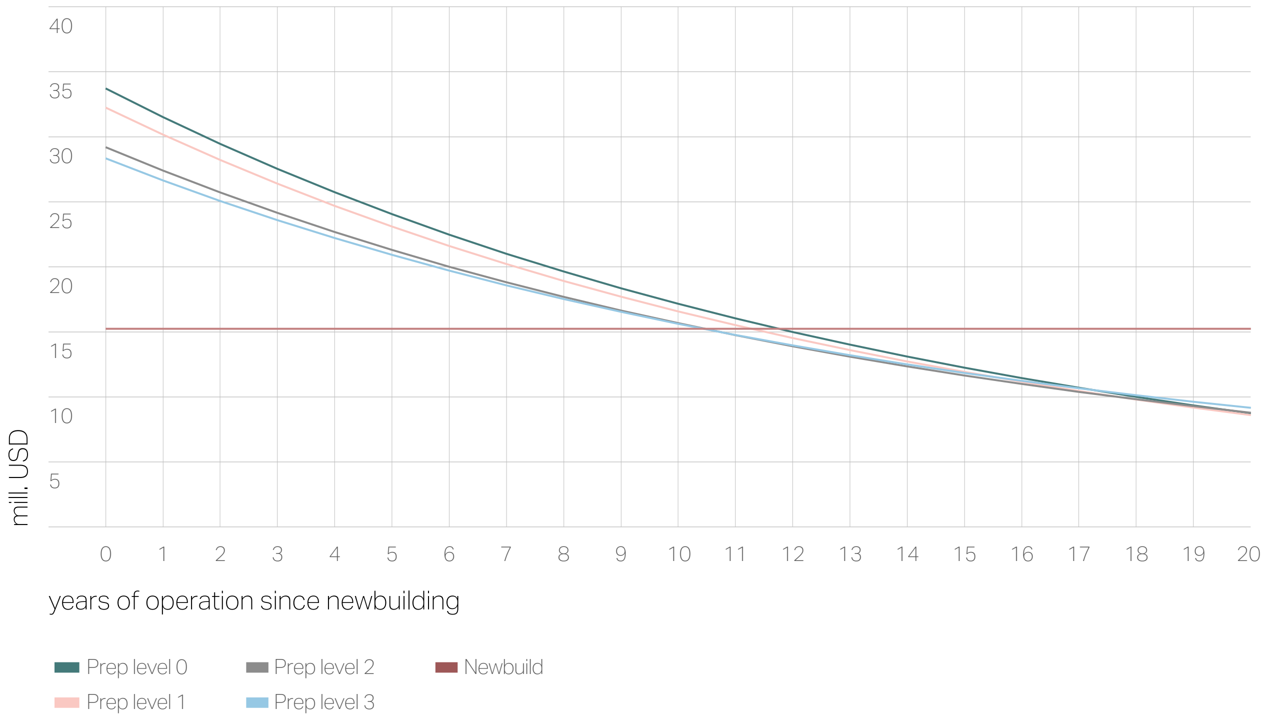
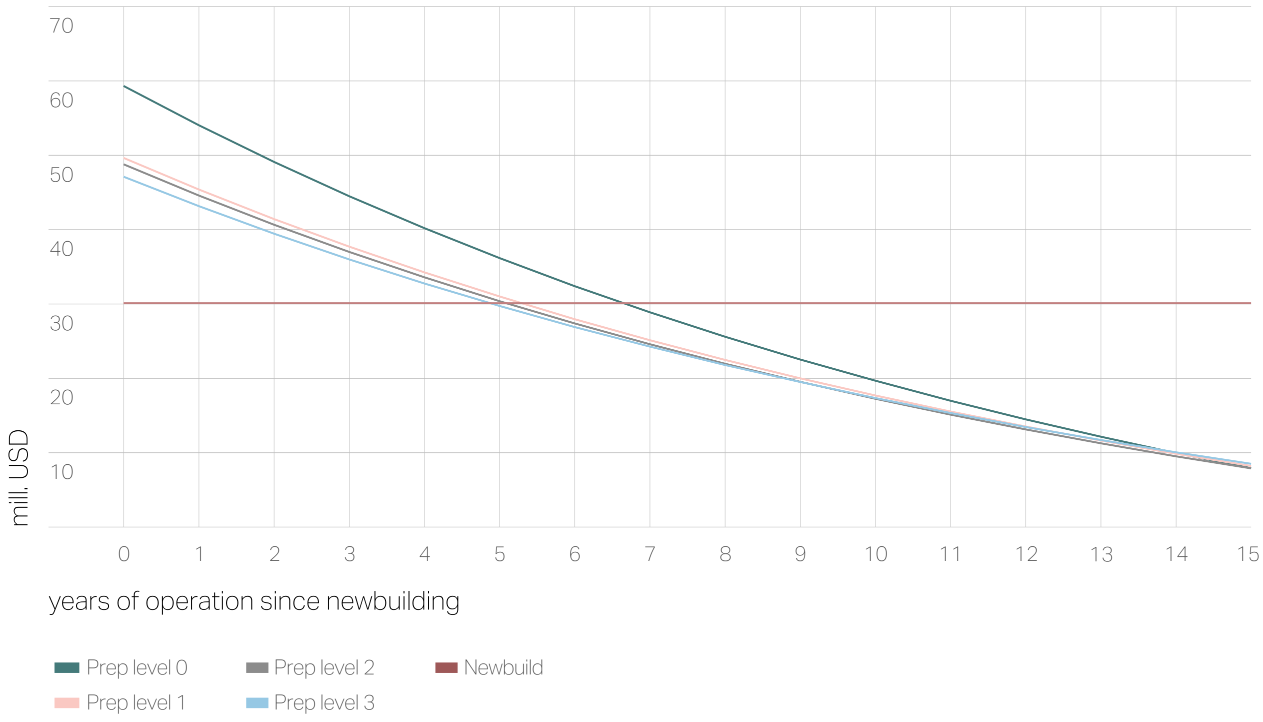


Figure 35: Present value of total LNG-ammonia conversion cost for a reduced-range VLCC tanker vessel.



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