ENGINE RETROFIT REPORT 2023:

Applying alternative fuels to existing ships

Contents

Foreword

Amid efforts to decarbonise shipping before 2050, ship technology developments often focus on newbuild vessels. But given the long working life of vessels, it is clear that many ships originally designed and arranged to be powered by fossil fuels are likely to remain in service by 2050, representing around 20% of the global fleet according to some forecasts. Decarbonising these vessels is therefore a crucial element of the maritime energy transition.

One solution is to retrofit vessels to use carbon-neutral or zero-carbon fuels. This may require changes to engine, tank, pipework, systems and structure. Engine designers have already prepared conversion packages for some fuels and are developing solutions for others. Projects to retrofit engines for methanol, for example, have begun for cruise and containerships, while interest in ammonia as a carbon-free fuel means that engine technologies are being developed with a view to application on existing vessels.

The decision to retrofit engines must be weighed against several other options, including drop-in net-zero, near-zero or absolute zero fuels, non-engine power technologies, or building new zero- or near-zero emissions tonnage. That decision will depend on the cost and feasibility of technologies, system integration and fuels, as well as the impact of new solutions on operating profile and costs, charter rates and carbon pricing exposure.

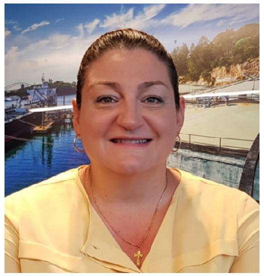
Many of those elements remain uncertain while net-zero or near-zero carbon fuels are scaled up and as a regulatory framework is established. Clarity on the capability to perform engine retrofits is also hard to find. Some engine technologies are ready to be installed, while for other fuels they have yet to be developed. Applying new fuel systems to ships built for conventional fuels also presents significant design challenges, as well as demanding new skills from repair yards.

This guide charts the current status of engine retrofit technology, integration capability and related compliance requirements. Using methanol and ammonia as examples, it highlights the technical, regulatory and commercial issues that will need to be addressed for engine retrofits to play a significant role in the decarbonisation of the global maritime fleet.

As one of the world's leading class societies and with deep expertise in alternative fuels and decarbonisation projects – including the world's first methanol engine retrofit project on the Stena Germanica in 2015 - Lloyd's Register is well placed to help ship operators select, plan and navigate a fleet decarbonisation pathway that ensures safety and compliance while deploying retrofit technologies on existing vessels.

This report examines the application of alternative fuel technology solutions to vessel conversions. For in-depth information on the properties of alternative fuels themselves – including their safety characteristics and emissions profiles – explore Lloyd's Register's Fuel For Thought series here:

www.lr.org/fuelforthought



Claudene Sharp-Patel,
Global Technical Director,
Lloyd's Register

EX Executive Summary

Decarbonising the existing fleet is an essential element of shipping's greenhouse gas reduction trajectory. Without it, there could still be up to 20,000 merchant vessels running on fossil fuels by 2050, putting the chance of net-zero emissions from the industry at risk.

This annual publication aims to track the state of engine retrofit demand, capacity and uptake. In this initial edition, methanol and ammonia are used as examples to consider the state of technology, compliance frameworks, systems integration capabilities and the business case for retrofitting. By monitoring the development of these elements across the years, the guide will highlight key areas of risk for ship operators, owners and other stakeholders considering vessel conversions for alternative fuels.

Retrofit potential

While fuel cost/availability and regulatory drivers remain uncertain, projecting demand is challenging. A maximum addressable market of 9,000-12,900 large merchant vessels was identified up to 2030, after which it is anticipated that all vessels will be built with net-zero or near-zero carbon fuels capability. In all likelihood only a small number of these vessels will eventually be retrofitted as the business case for converting older vessels (beyond ten years) and smaller vessels will likely remain challenging. However, converting even a fraction of this potential market will require new capabilities and technologies from ship designers, shipyards and operators.

Fleet readiness

Fleet readiness for zero-emission fuels is growing, with 225 ammonia- and 120 methanol-ready vessels in service or on order at the time of publication. While 'fuel ready' class notations certify that particular aspects of alternative fuel conversions have been approved in principle, or even approved and implemented – and that the required level of safety can be achieved, subject to the work being carried out correctly - they do not necessarily include detailed design, costs and conversion plans. This leaves uncertainty over the costs and timescales required to make a vessel labelled as 'ready' capable in practise of operating on zero-carbon fuel. To assist stakeholders in planning retrofits more effectively, a Zero Ready Framework has been proposed to provide additional clarity over vessel readiness. By committing to only financing, building and ordering vessels that meet a clearly defined readiness level by specified dates, stakeholders can better manage the risks of the energy transition across existing fleets.

Technology readiness

Fuel conversion packages have yet to be deployed at scale and in many cases remain under development. The cases of methanol, which is already used as a ship fuel, and ammonia, which is emerging as a fuel candidate, have been studied to explore technology readiness for engine conversions. The guide contains an in-depth review of the current state of retrofit solutions (Section 5), as well as a Technology Readiness Level indicating the state of readiness for commercial application.

Methanol engine conversions are on the cusp of being introduced at wider scale following an outlier early adoption in 2015. At least two suppliers are ready to install engine retrofit packages imminently, with more in advanced stages of development.

Ammonia engine conversions are a more challenging and more distant prospect. Newbuild engine concepts have yet to be finalised and the safety issues around using ammonia as fuel, already expected to be challenging on vessels built for that purpose, will mean more complexity around retrofit packages and their installation.

TRL	Level description
1	Basic principle observed
2	Technology concept formulated
3	First assessment of feasibility concept and technologies
4	Validation of integrated prototype in test environment
5	Testing prototype in user environment
6	Pre-production product
7	Low scale pilot production demonstrated
8	Manufacturing fully tested, validated and qualified
9	Product fully operational

Technology	TRL
Two-stroke engine retrofit package, methanol	4
Four-stroke engine retrofit package, methanol	5
Methanol fuel handling and storage	5
Two-stroke engine retrofit package, ammonia	3
Four-stroke engine retrofit package, ammonia	3
Ammonia fuel handling and storage	3

System integration challenges

While conversions for alternative fuels depend on engine technology readiness, the bigger challenge is integrating the wider fuel system on existing vessels. The key issues can be summarised as:

1. **Tanks:** Larger tank volume requirements for fuels with lower energy density mean that finding the appropriate place for tanks, meeting safety requirements with minimal impact on structural integrity and cargo capacity, is challenging.
2. **Fuel preparation:** Some existing vessels designs may make it difficult to find a contained space for the fuel pumps and valve train that is close to the engine room.
3. **Piping:** The added cost and bigger dimensions of double-walled fuel piping means that ship conversion pipe routings should be planned to minimise the disruption to ship structures (such as bulkhead penetrations).
4. **Safety arrangements:** Venting, purging, ventilation and fire/gas leak detection and prevention all add to the complexity of applying alternative fuel systems to existing ship designs.

Across all these areas, designers need to maintain a focus on safety and minimising the exposure of crew to toxic and flammable fuels.

Regulatory issues

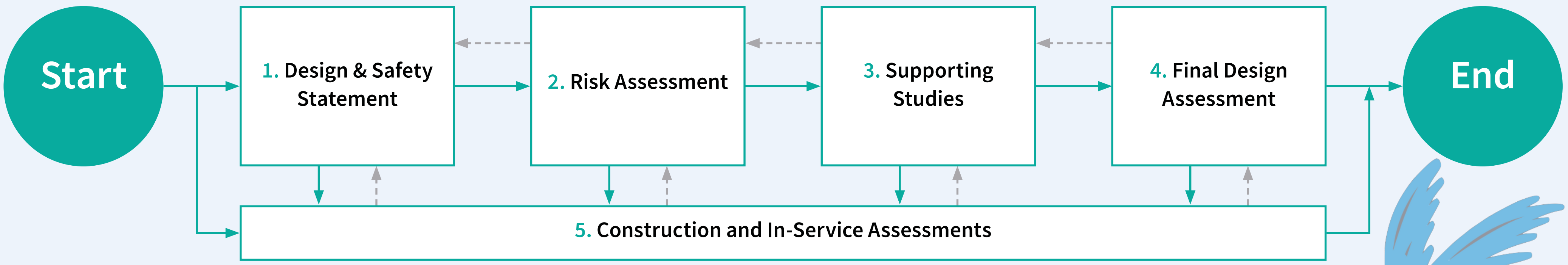
Current IMO requirements for the use of methanol as fuel are given under the interim guidelines MSC.1/Circ.1621, which includes goals, functional requirements, detailed prescriptive requirements together with a requirement to undertake a risk assessment. Currently there are no IMO requirements in place for ammonia as fuel and therefore approvals are risk-based rather than prescriptive, meaning that in addition to the normal rigours of design appraisal a robust risk management process needs to be applied. The approval process is outlined in the IMO Guidelines for Approval of Alternatives and Equivalents (MSC.1/Circ.1455).

Lloyd's Register have developed a Risk Based Certification (RBC) process which is consistent with and based on MSC.1/Circ.1455, and other related IMO guidelines, yet equally applies to non-SOLAS projects. RBC is used where risk assessment is required to inform certification and provide confidence in new, novel and alternative designs.

For an alternative fuel project, the risk-based process needs to meet the mandatory requirements in SOLAS Reg.II-1/55 (including the IGF Code), the guidance in MSC.1/Circ.1455, and be undertaken in accordance with the LR RBC process. Refer to Section 5 Classification Rules for further information on the application of RBC.

A further regulatory issue for engine retrofits is NOx certification required under MARPOL after a major conversion. The regulations require a converted engine to be recertified for NOx emissions. If an identical certified engine does not exist, as will be the case for many early retrofits, recertification means testing at sea or testing a suitable engine at testbed, which can be challenging. This issue is under discussion at IMO's Pollution Prevention and Response Committee.

Risk Based Certification (RBC) Process



Human Factor elements

The impact on crew working with new fuels needs careful consideration and must not be overlooked when equipping an existing vessel for alternative fuels. Working on a vessel with these fuels, as well as operating and maintaining new equipment, entail new risks. Assessment of human factors (Section 8) goes beyond working conditions and schedules to examine design and safety procedures to ensure that these risks are minimised. This should include:

- **Ergonomics:** Ensuring the design of a vessel and its components address the intended users' capabilities and limitations given the operating circumstances and conditions.
- **Roles and responsibilities:** Demonstrating that responsibilities of crew are clearly defined and that personnel can safely perform activities with the resources provided.
- **Competency and training:** Crew have appropriate training for the relevant fuel, any new technologies and existing skills with heightened relevance, such as maintaining situation awareness and recognizing potential hazards.
- **Resourcing:** Enough crew are available to safely perform activities such as navigating, mooring, ship integrity and emergency response.
- **Procedures and processes:** How should control processes be developed to address the criticality of the risk, and how is delivery managed to promote adherence from the crew.
- **Occupational health:** Consideration of risks inherent with fuels and new systems, and how these can be mitigated via design, procedure and personal protection equipment.
- **Process safety hazards:** How to manage, and promote early recognition and response to, new circumstances where human activities may contribute to, exacerbate or prevent recovery from a hazard.

Retrofit Capability and Capacity

Integrating alternative fuel systems on existing ships will demand new skills from repair yards. Among the skills cited by ship designers **(Section 7)** are:

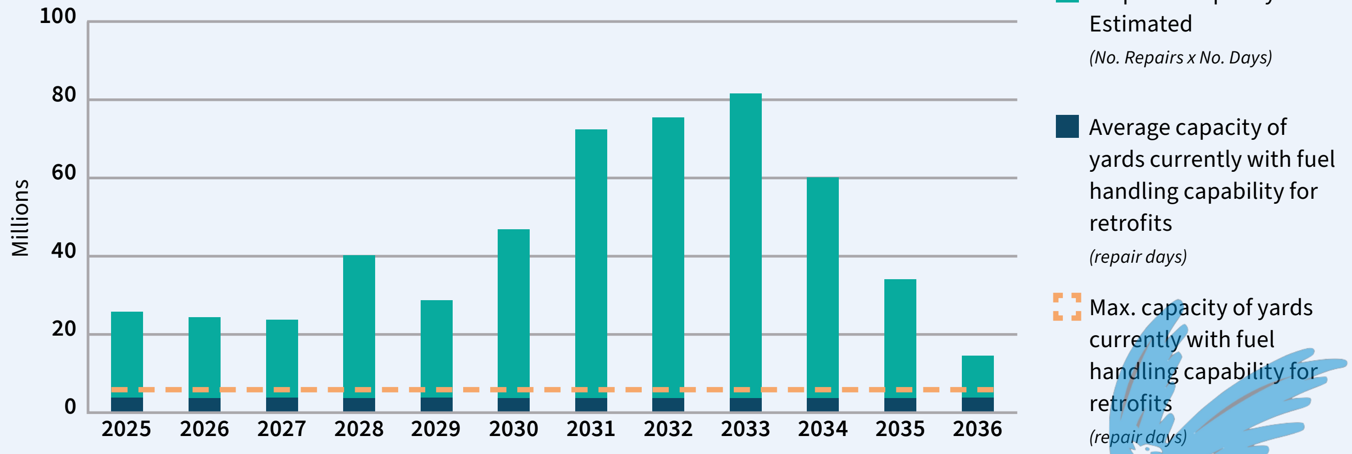
Naval architecture: The design and location of system elements including tanks, fuel preparation rooms and piping needs careful consideration to comply with safety requirements, particularly the need for venting and hazardous zones. Assessing the impact of each part on the vessel's structural strength and stability is also critical.

Electrical engineering: Enhanced monitoring (leak and fire detection), automated mitigation systems (including purging, firefighting, venting and ventilation), as well as more complex regulation of the fuel chain place new demands on vessel electrical and automation infrastructure. This will require greater electrical engineering skills from yards in order to adapt or where necessary install entirely new systems.

Fuel handling: Especially during the commissioning and testing stages of the retrofit project, yards will need to have the capacity to handle alternative fuels. Given the limited number of existing alternative fuelled vessels in operation and their relative recent introduction – limiting repair yards' exposure to these vessels – this places a constraint on the number of repair yards currently capable of handling these projects.

These skills requirements mean that only a few repair yards can be assessed as currently being capable of performing fuel conversions. Our modelling identified 16 yards with a maximum capacity of around 300 vessel conversions a year in total.

Required yard capacity for fuel conversions (No. Repairs x No. Days)



Techno-economic analysis

The results of techno-economic modelling **(Section 9)** indicate that using renewable methanol or ammonia today would more than double the fuel costs for vessels in all segments, at a global carbon price of US$100 per tonne. For vessels with greater fuel consumption – notably the large cruise and container ships - the additional fuel costs in a year approach the price of a conventional newbuild vessel.

The low-cost scenario, in which both ammonia and methanol decrease in price by close to 50% and the carbon price reaches an extremely high US$350, is just beyond the tipping point at which alternative fuels become cheaper than continued use of conventional fuels.

The cost of retrofitting is currently uncertain and will have a significant impact on the business case for both owner and operator. As an example, the owner of a Newcastlemax Vessel who wished to amortise the cost of a US$10 million retrofit over ten years would need to charge an 11% premium on current charter rates (at time of publication), representing a US$2,907 increase. This amounts to an extra US$1 million a year on the charter cost for the operator, on top of the cost of the new fuel.

Investment readiness

Current projects and market interest in engine retrofits indicate differing levels of appetite across vessel segments. Combined with the insights above on technology development, retrofit capabilities and cost, Lloyd's Register formulated an Investment Readiness Level indicator for four segments – cruise, containers, tankers and bulk carriers.

The results demonstrate that although some sectors – notably cruise and container ships - are close to adopting methanol fuel retrofits, the investment case across all segments is still very immature. For ammonia, the business case for retrofitting remains hypothetical only until initial use cases are observed.

Conclusion

This report outlines the challenges that lie ahead for the industry if alternative fuel engine retrofits are to play an important role in the decarbonisation of shipping. The technologies and capabilities for retrofits are emerging. While the business case for most vessels remains to be seen, that could change very quickly as more clarity emerges on fuel costs, availability and regulatory drivers including carbon pricing.

Alternative fuels use as a whole is in its early stages, the application of these fuels to existing vessels even more so. As with any new use of technology, managing risks to crew, assets and operations is a fundamental first step. The challenges identified in this report – and the progress tracked in future editions – highlight the work that remains to be done in ensuring that those risks are mitigated.

Methanol retrofit pioneer returns after decade of discovery

Since the landmark conversion of the Stena Germanica in 2015, ship operator Stena Line has continued to embrace the potential of the fuel to reduce emissions across its existing fleet. The company will convert further vessels in 2025, by which time it will have amassed ten years of experience on the original ro-pax.

Retrofitting in 2025 is a very different prospect to the early challenges that Stena faced, says Oliver Davidsson, Fleet Sustainability Coordinator at Stena Line.

"Stena had already been public about the potential of methanol and already had some experience after a project in which it has bunkered methanol and converted it to dimethoxymethane [DME] onboard. But at that stage there were no specific IMO or class rules, and component selection was a case of trial and error with suppliers; the information available on materials was not entirely reliable."

With no rules, the Germanica conversion team adopted a risk-based approach, with Lloyd's Register coordinating large stakeholder meetings with members including ports, national maritime authorities and technology suppliers, notably Wärtsilä, which was responsible for converting the vessel's engines (and will convert the forthcoming vessels). Today, the risk-based approach still applies as methanol-fuelled vessels – and conversions in particular – remain relatively new. But the introduction of prescriptive rules under IMO's IGF Code and from class societies has clarified many of the risks.

One example is tanking arrangements. On Germanica, the methanol tanks were built inside ballast water tanks and protected by a water-filled cofferdam to eliminate the risk of leakage. Today the safety rules around methanol storage require cofferdams around the tanks, except on those surfaces bound by shell plating below the lowest possible waterline , a far less challenging proposition.

Operational experience has also delivered insights into safe use. For example, the location of leak detection is paramount. Davidsson recalls that the original leak detection arrangements on Germanica had to be reconfigured after detectors were placed in some cases above pipes or high on walls in machinery areas. That would work with gases or vapour but as methanol is liquid at ambient conditions, leaks are more effectively detected at low levels.

As Stena's experience has grown, the company's belief in methanol as a solution has also increased. While the original Germanica project was driven by the need to meet new sulphur emission requirements, today it is greenhouse gas emissions that are propelling Stena's investment in methanol retrofits. Methanol produced from renewable feedstocks – in Sweden there are emerging projects using electricity from wind and pyrolysis – can reduce the fuel's greenhouse gas intensity to nearly zero, helping operators to plan compliance with forthcoming IMO and regional targets, as well as optimising exposure to carbon pricing.

The past eight years have seen all parties in the original project build on their early learnings. The company will again work with Wärtsilä to deliver a turnkey technical solution including fuel supply, engine conversions and automation. The Port of Gothenburg and Stena recently conducted the first ship-to-ship bunkering of methanol, adding new operational flexibility to the deployment of the fuel. And Lloyd's Register has developed full class rules and guidance that will make future conversions safer and less onerous.

Experience is important, and it seems as though Lloyd's Register has the experience when it comes to retrofits. When we speak to some suppliers and partners who have not been involved in these projects, it feels like we are having those initial discussions about the Germanica over again."

Oliver Davidsson
Fleet Sustainability Coordinator at Stena Line.

1 Fleet and technology readiness

Assessing the market for engine retrofits, the state of fleet readiness to deploy them and the readiness of the technologies to be adopted.

A significant number of vessels built to use conventional fuels will need to be decarbonised by 2050 if shipping is to meet its greenhouse gas emission reduction targets. A proposal made by Japan[1] during IMO talks on greenhouse gas emissions projects that, based on industry fleet development projections, around 16,000-20,000 fossil-fuelled vessels over 5,000 gross tonnes – up to a third of the large merchant fleet - will need to become zero-emission vessels by 2050 in order for shipping to reach net-zero emissions. A review of the wider global IMO-regulated fleet by UMAS and E4tech[2] anticipates that 15,000-16,000 vessels, roughly 15% of the fleet, will require retrofitting with zero-emissions technology by 2050.

These vessels will not all retrofit engines for alternative fuels. Drop-in net-zero or near-zero carbon fuels that can be used in existing engines, alternative power sources such as electricity or direct wind propulsion, and carbon capture and storage all compete with engine conversions as potential solutions for decarbonising vessels in service. Vessel owners must also weigh the benefit of decarbonising existing vessels against the option of replacing tonnage with zero-emission vessels. But with the potential of retrofitting engines for net-zero or near-zero carbon-neutral fuels – such as renewable ammonia and methanol – becoming a reality, it is likely to become an important part of the solution for this large segment of the global fleet.

Assessing fleet readiness

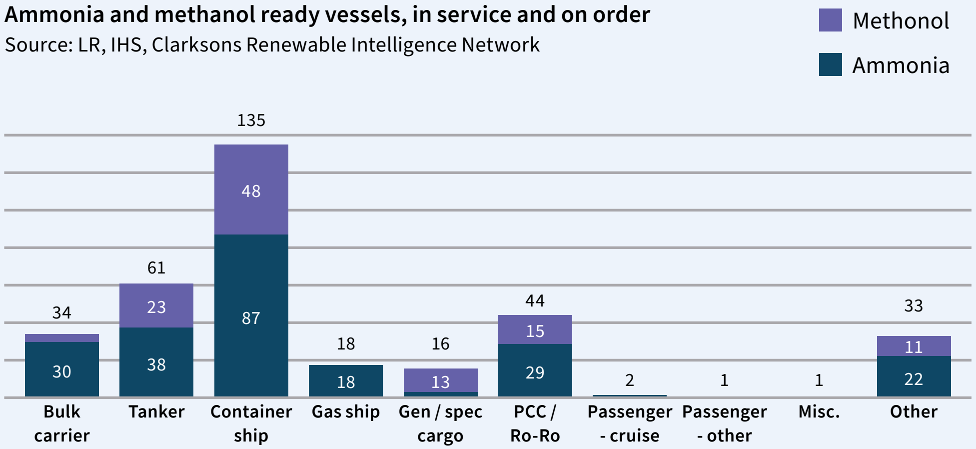
The number of 'fuel-ready' vessels in service and on order gives an early indication of the potential uptake of engine retrofits. These vessels may hold a 'ready' recognition, such as a class notation or descriptive note, which indicates from a Classification perspective only that no insurmountable barriers exists for the future deployment of the recognized fuel. Further work will be required to make these vessels alternative fuel capable.

Looking at two of the most widely discussed alternative fuels, methanol and ammonia, published data suggests that there are 477 fuel ready and capable vessels in service and on order (to 3 May 2023). Of these, 249 are methanol ready/capable and 228 are ammonia ready/capable. However, the level of readiness is not generally defined and therefore the work required to convert from ready to capable is expected to vary widely.

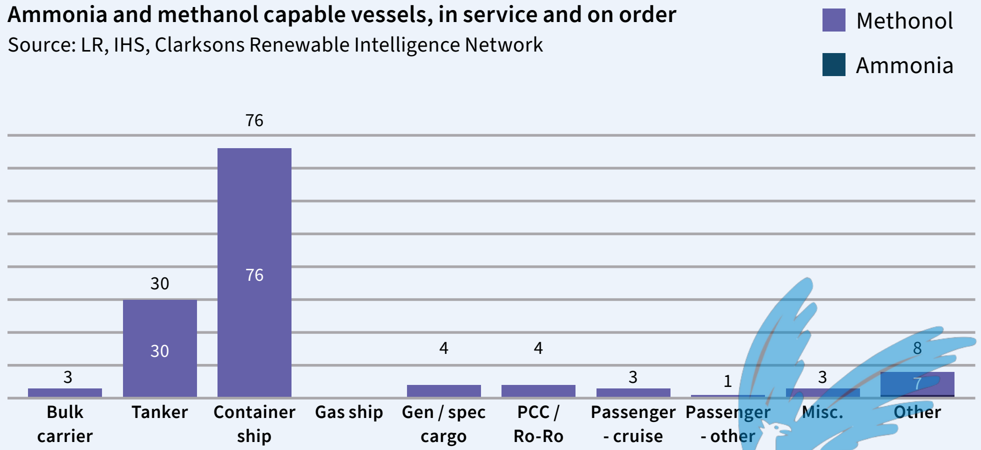
If all the methanol- and ammonia-ready vessels in service and on order today were converted, that would entail a total retrofit market of 345 vessels. However, the true size of the market that will need to be converted to reach zero emissions by 2050 is much higher. This suggests that a deeper appraisal of vessel readiness is needed to understand exactly which vessels are retrofit candidates, as well as the work and investment that will be needed in the conversion.

As vessel readiness is only a preliminary and incomplete indicator of the demand for alternative fuel retrofits, more analysis is needed to ascertain a realistic approximation of the potential market for engine conversions.

Ammonia and methanol ready vessels, in service and on order
Source: LR, IHS, Clarksons Renewable Intelligence Network



Ammonia and methanol capable vessels, in service and on order
Source: LR, IHS, Clarksons Renewable Intelligence Network



Understanding real readiness: The Zero Ready Framework

Vessel conversion is technically complex and involves significant costs. It may involve changes in layout, structural modifications to the vessel and replacement of pipework and systems. Class readiness notations certify that the required level of safety can be achieved, subject to the work being carried out correctly and other specific requirements being met, but do not include detailed design, costs and conversion plans.

Retrofit costs will be significantly influenced by the level of readiness, the scope of the conversion and the rules to be applied. For this reason, the LR Maritime Decarbonisation Hub has developed the **Zero Ready Framework**, which aims to provide the clarity needed to support strategic planning and investment in assets. The framework as described in the table, enables a better understanding of the state of readiness of vessels for conversion and the costs involved in delivering a zero-emissions vessel.

By using this framework in development of strategies and plans – as well as committing to only financing, building and ordering vessels that meet a clearly defined readiness level by specified dates – business can manage the risks faced in the energy transition and demonstrate climate commitments to customers, business partners and end consumers.

Zero Ready Framework

	Readiness standard		Criteria		
	Name	Description	Capabilities	Additional requirements	Comments
1	Near net zero GHG vessel	Capable of bunkering and operating for all onboard energy usage in all operating modes.	All required equipment installed and commissioned.	Capabilities apply to all energy sources onboard. Cannot be powered by fossil fuels.	-
2	Low GHG vessel	Capable of bunkering and operating for primary propulsion in the mandatory of operating modes.	All required equipment installed and commissioned.	Capabilities apply to primary propulsion.	Fossil pilot fuels acceptable. Dual/multi-fuels acceptable.
3	Conversion under preparation	Primary propulsion capable of using fuels in scope. Some key components already installed but not yet commissioned.	Minimum requirements: • Engine retrofitted for fuel in scope. • Fuel storage tank in place.	Capabilities apply to primary propulsion.	-
4	Designed for conversion	Fossil fuel vessel with high level of detailed design for conversion.	-	Capabilities apply to primary propulsion.	Detailed design is preferred to high level. Ideally costings for conversion provided.
5	Potential for conversion	Fossil fuel vessel with main engine that could fuel in scope, if retrofitted.	-	Retrofit pack available for main engine.	Will become the norm as dual or multi-fuel engines become the default.
	Fossil fuel only	Has no possibility of retrofit.	None	None	-

Assessing the market for engine retrofits

Modelling performed by LR reveals a potential market of 9,000-12,900 large merchant vessels that could consider engine retrofits to decarbonise by 2050. Key factors influencing the size of the market and the timing of retrofits include the date by which shipping begins building only zero-emission vessels, as well as the age at which owners or operators decide to retrofit their vessels.

Identifying retrofit candidates

To explore the number of candidates for engine retrofits in the global merchant fleet, the following initial assumptions were made:

1 Within the next few years, the shipbuilding market will receive a strong signal to build only zero-emission vessels. This could be a prescriptive requirement from the IMO, for example, or a carbon-pricing measure that makes alternative fuel use significantly more attractive than continuing to use fossil fuels. This provides a date from which zero-emissions vessels will be built. Two potential starting periods are modelled:

   a Starting from 2027, zero-emission vessel building grows exponentially to 2032, by which time only zero-em-ission vessels are built.

   b Starting from 2030, zero-emission vessel building grows exponentially to 2035, by which time only zero-emission vessels are built.

2 The global shipping industry's target for decarbonisation will be advanced to aim for net-zero emissions from international shipping by 2050 at the latest. For simplicity, intermediate targets are excluded from the model.

3 Vessel retrofits for methanol and ammonia will be available from 2025 and 2027 respectively.

Applying these dates to industry fleet growth projections identifies how many vessels designed for conventional fuels will still be in operation by 2050.

Several of these vessels will not use engine conversion to reach zero emissions. To find a vessel population where retrofit uptake can be accurately analysed, the model includes only container ship, bulk carrier and tanker vessels.

After discussions with technology providers, a range of further criteria are applied to identify viable vessels for retrofit. These include:

- Vessels with electronically controlled engines
- Vessels from the current fleet with a maximum age of eight years
- Vessels with the following minimum size:
  - Container ships: 8,000 TEU
  - Tankers: 50,000 DWT
  - Bulk carriers: 150,000 DWT

While electronically controlled engines are a technical pre-requisite of applying retrofit solutions, age and size requirements are related to the business case for conversion. It can therefore be reasonably assumed that, as retrofit technology and installation capability increases in maturity, the business case will broaden to include older and smaller vessels. This transition is modelled by assuming that initially, all vessels will meet the above age and size criteria, with those restrictions being lifted five years after retrofitting begins. In another scenario, retrofit uptake is modelled for all merchant vessels without this transition.

Vessel age at retrofit

The age at which a vessel is retrofitted is an important factor in the business case for a conversion. The younger a vessel is when retrofitted, the more years in service are remaining for it to earn back investment on the retrofit. A retrofit for an older vessel could extend its service life by keeping it within emissions compliance but would need to be weighed against the cost of early scrapping and replacing with a newbuild zero-emissions vessel.

Two different assumptions for the age at which vessels will be retrofitted under the current model:

1 Maximum age of 10 years: Under this assumption, maximum age for retrofits is applied across vessel segments based on vessel values, but do not exceed 10 years. This aims to reflect the current commercial case for retrofitting.

2 Maximum age of 15 years: This scenario assumes that wider commercial case for retrofitting can be found, with uptake of retrofitting across the vessel population evenly distributed at 5, 10 and 15 years.

Forecasting fuel uptake

The most complex element of modelling retrofit uptake is making assumptions on which fuels vessels will adopt. While methanol and ammonia are currently viable fuel candidates for moving to zero-emissions, there are multiple other fuels that could be chosen, as well as technologies that could be applied once developed (such as carbon capture).

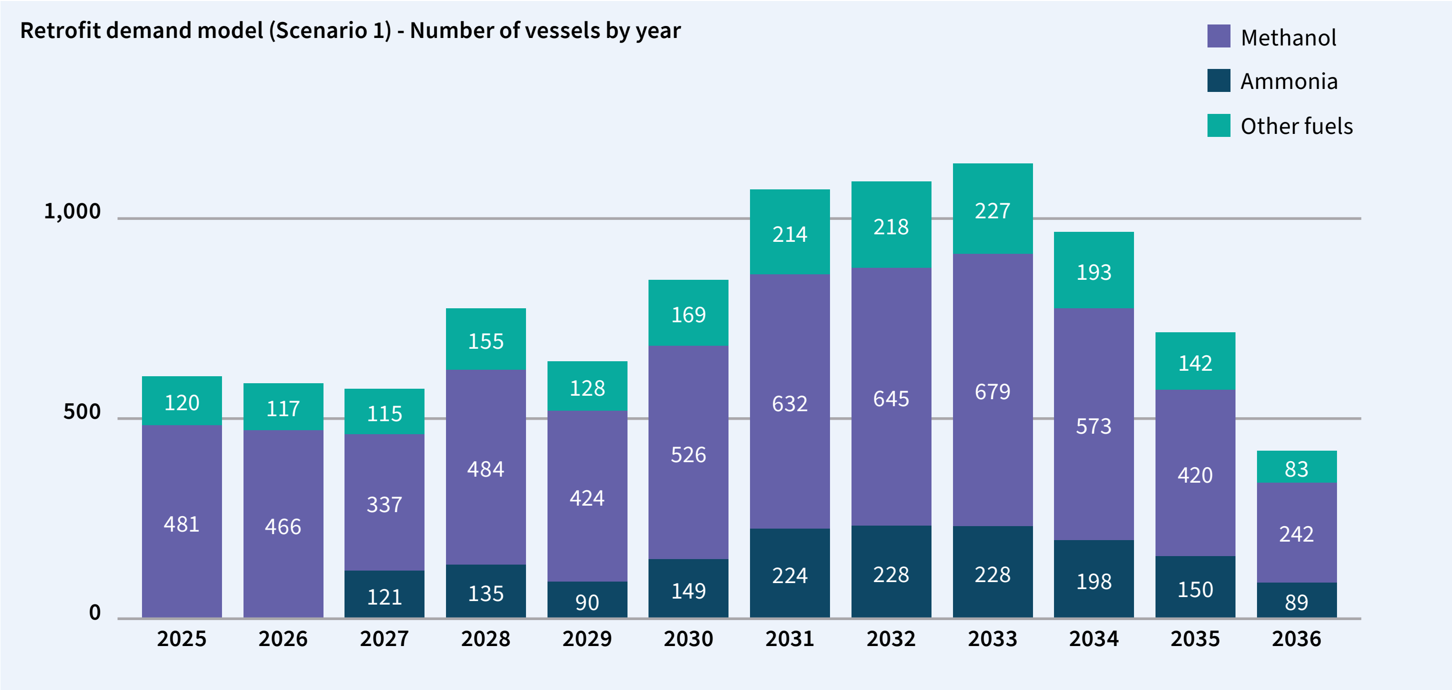
To represent these alternatives, the model assumes that 20% of all candidates identified will opt for decarbonisation solutions beyond methanol and ammonia on current insights into fuel sentiment in specific markets. For example, bulk carriers of 100,000 DWT and bigger are assumed to adopt mainly ammonia, due to current indications that a substantial production of and market for ammonia will exist on some trades, including between Australia and China. Meanwhile handysize chemical and product tankers are assumed to adopt mainly methanol due to potential synergies with their cargoes and the fact that their use of ports near heavily populated areas makes ammonia adoption more challenging.

It should be noted that these assumptions are based on the very preliminary insight into fuel uptake currently available. As such they are likely to change significantly as the scale up and industry uptake of alternative fuels advances. As already discussed, there are multiple alternative solutions that are each advancing in maturity. The models described below can therefore best be viewed as a representation of the maximum number of vessel candidates for methanol and ammonia retrofits in the global merchant fleet, rather than as a prediction of actual uptake.

Model scenarios

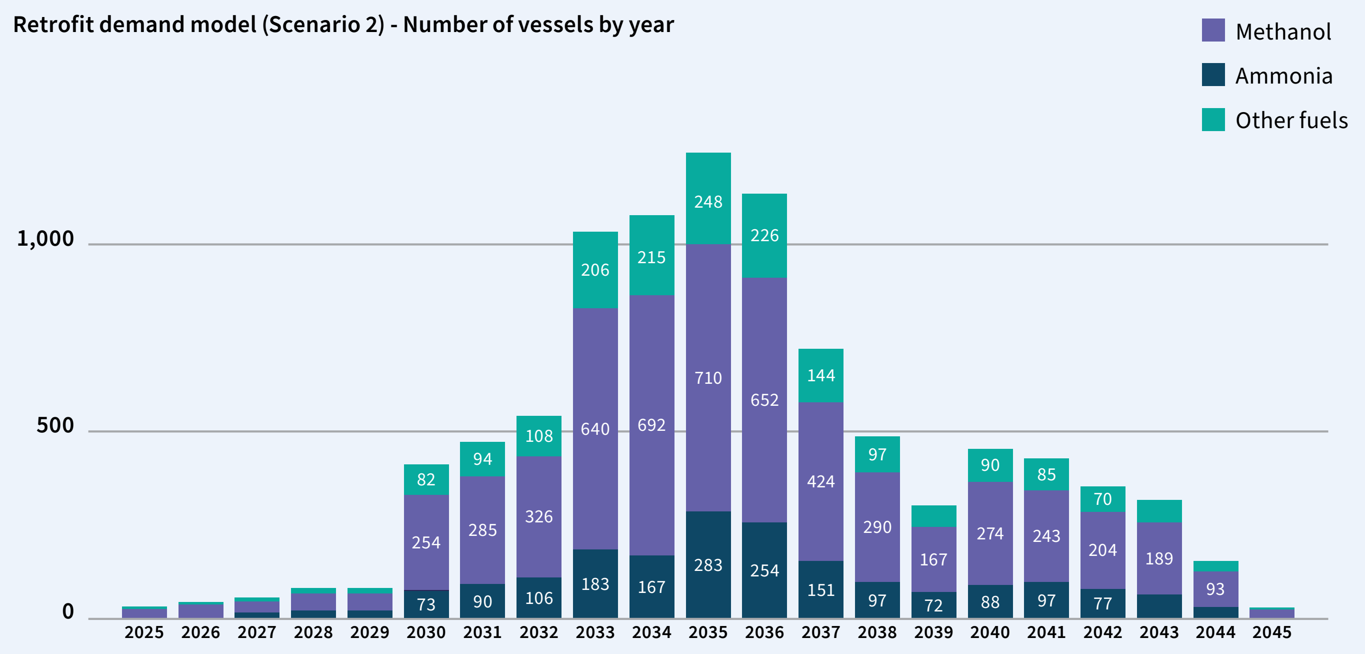
Based on the above assumptions, three scenarios are modelled:

1 **Early adoption of zero-emission newbuilds, maximum retrofit age of 10 years, no delay in uptake on smaller vessels**



This scenario envisions that the transition to building only zero-emission vessels begins in 2027. This leaves a population of around 9,400 conventionally fuelled vessels still trading in 2050 that are candidates for retrofits. Under this scenario, around 5,900 vessels are candidates for methanol retrofits while 1,600 are candidates for ammonia retrofits. The ten-year age limit on converting vessels – and the fact that for some vessel types a retrofit is only likely to be viable at five years - means that the retrofitting period is compressed between 2025, when methanol conversions begin, and 2036, when the last conventionally fuelled vessels (built in 2031) are converted.

2 Early adoption of zero-emission newbuilds, maximum retrofit age of 15 years, 5-year delay in uptake on smaller vessels



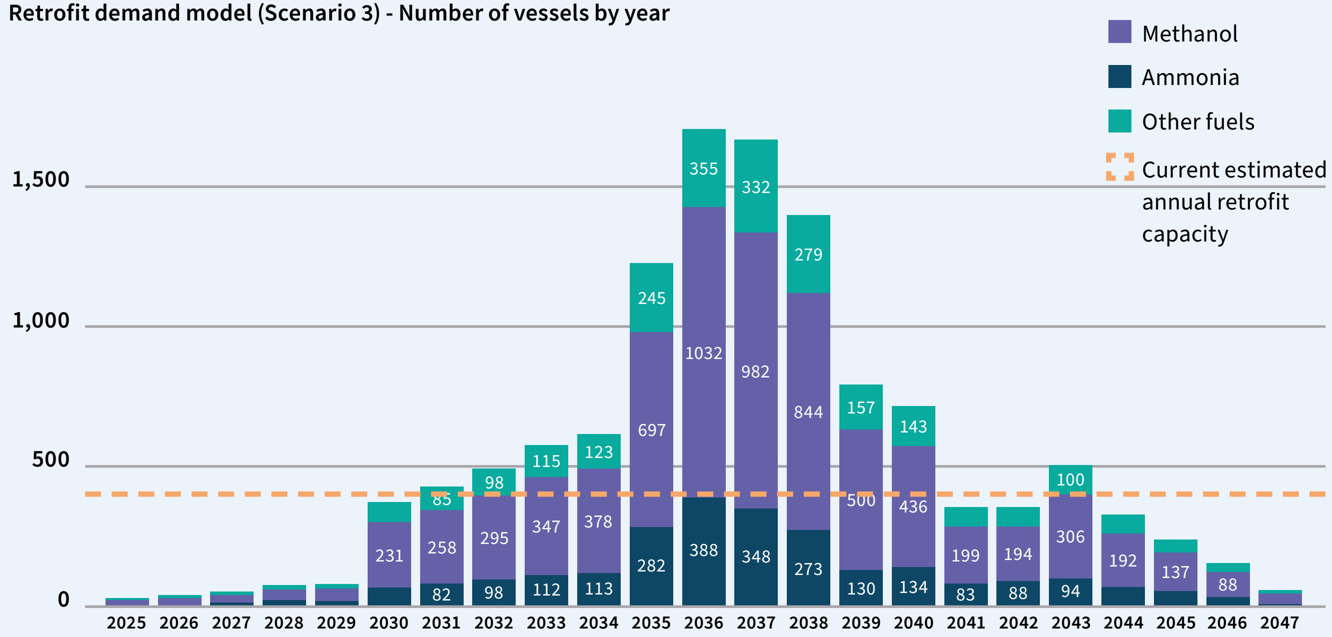
Under Scenario 2, the same population of retrofit candidates is identified as in Scenario 1 because the starting date from which zero-emission newbuilds are built is the same. However, two factors affect the time period over which retrofits could potentially be taken up.

First, a five-year delay is assumed before the criteria for retrofit candidates can be extended so that smaller vessels are viable. This models a slower advance in the maturity of retrofitting technology and capability. The result is a gentler initial uptake followed by a dramatic increase in retrofitting activity from 2030, when smaller vessels become viable retrofit candidates.

Second, vessels are retrofit candidates up to 15 years of age, rather than a maximum of 10 years in Scenario 2. This means that the last retrofits, on vessels built for conventional fuels in 2031, take place in 2045. There are no retrofits in 2046 because all non-zero-emission vessels built in 2031 were in vessel types where retrofits are only viable at ten years or below.

3 Late adoption of zero-emission newbuilds, maximum retrofit age of 15 years, 5-year delay in uptake on smaller vessels

Retrofit demand model (Scenario 3) - Number of vessels by year



Scenario 3 shows the impact of a late move to zero-emission newbuilding on the retrofit market. The retrofit age limit of 15 years and the five-year delay in applying retrofits to smaller vessels are the same as Scenario 2, but zero-emission newbuilding starts in 2030 rather than 2027. From 2035, only zero-emission newbuild vessels are built.

The result of the delay in zero-emissions newbuilding is that a further 3,300 retrofit-candidate vessels built for conventional fuels remain in service by 2050, taking the total potential market for engine retrofits to 12,270. Of these, around 7,300 could retrofit methanol-fuelled engines, while 2,500 could opt for ammonia.

Given the late adoption of zero-emission newbuilds, that last conventionally fuelled vessels are built in 2034. This means that, considering the maximum age of 15 years at the point of retrofitting, the last vessels could be converted for methanol and ammonia in 2049. But as the vessels built in 2034 were only deemed viable retrofit candidates at ten years or younger, the actual final year of the retrofitting phase is 2047.

Retrofit demand model summary

The retrofit demand model highlights a maximum potential market for methanol and ammonia retrofits (global merchant fleet excluding LNG-fuelled vessels and gas carriers) of 12,900 vessels. The three scenarios for uptake of methanol and ammonia engine retrofits highlights two key market dynamics:

- The vessel age at which retrofits are deemed viable has a big impact on the timing, but not the volume, of retrofit demand. The same population of vessels are retrofit candidates, but with lower retrofitting ages, the timeframe in which retrofitting takes place is compressed. This could have a significant impact on the capability of shipyards to handle demand.
- The date from which zero-emission newbuilds only are built is the biggest factor in determining the number of potential retrofit candidates. The later the decision comes for the industry to build zero-emission vessels, the more demand there will be for engine retrofits.

Assessing technology readiness

While engine retrofit technology is at a relatively mature stage and on the verge of wider industry adoption, there are significant developments needed both in engine development and in fuel handling and storage before ammonia can be considered ready for adoption.

Understanding the current state of retrofit technology development is another key factor in assisting ship owners and other stakeholders with their decisions for decarbonising existing vessels. Using the nine-point Technology Readiness Level (TRL) scale already in use by many organisations[3], LR has assessed the different technologies involved in engine retrofits: retrofit packages for four-stroke and two-stroke engines, and fuel handling and storage technology.

TRL	Level description
1	Basic principle observed
2	Technology concept formulated
3	First assessment of feasibility concept and technologies
4	Validation of integrated prototype in test environment
5	Testing prototype in user environment
6	Pre-production product
7	Low scale pilot production demonstrated
8	Manufacturing fully tested, validated and qualified
9	Product fully operational

The assessments below are based on an evidence-gathering process involving both engine designers and LR technology experts. They provide a basis from which the further development of the technologies towards commercial application can be tracked.

Engine retrofit packages

An engine retrofit package consists of the on-engine fuel injection and combustion control components needed for the new fuel, as well as any adaptations to lubrication and cooling concept needed for the new combustion environment. These replace or supplement the existing fuel components on the original engine, mainly on the cylinder head. In-cylinder components and piping will also need to be matched to the characteristics of the new fuel, including pressure of supply/injection, resistance to corrosivity and any measures to prevent fuel leakage.

In the case of four-stroke engines, retrofitting is not the only option for converting a vessel for alternative fuels. Vessels can also be re-engined, replacing the existing engines with newbuild engines capable of using the required fuel. The availability of this option depends on the existence of a newbuild engine and is not reflected in the TRLs below.

Technology	TRL
Four-stroke engine retrofit package, methanol	5
Four-stroke engine retrofit package, ammonia	3
Two-stroke engine retrofit package, methanol	4
Two-stroke engine retrofit package, ammonia	3

Four-stroke engine retrofit packages for methanol have already been deployed in service, namely on the Stena Germanica cruise ferry in 2015. Newbuild methanol engines, which provide a base for development of retrofit solutions, are already in service. There are current vessel projects that will introduce methanol engine retrofits within the next two years. In some cases, engine designers are adopting a retrofit-first approach, aiming to introduce retrofit solutions that can be applied across the portfolio before developing methanol capability for specific engine sizes. This advanced state of development takes four-stroke methanol retrofit technology to **TRL 5.**

Four-stroke engine retrofit packages for ammonia have yet to be introduced to the market at prototype stage. This follows from the fact that newbuild engine technology concepts have yet to be finalised or applied. Of the engine designers interviewed by LR, one has had a test-engine operating for more than two years, while another has yet to finalise the fuel injection concept. As the first assessment of retrofit package concepts has yet to be completed, four-stroke ammonia retrofit technology sits at **TRL 3.**

Two-stroke engine retrofit packages for methanol are due to be introduced imminently, based on the designs of methanol-fuelled newbuild engines that have been in service for several years. Orders have been placed for up to 80 retrofits and interviews with engine designers revealed strong immediate commercial interest in retrofitting two-stroke engines. One developer is advancing its retrofit technology project to be able to offer retrofit technology almost as soon as newbuild methanol capability has been achieved. However, with no pilot installation yet, there is no in-service prototype for two-stroke methanol retrofit packages, placing them at **TRL 4.**

Two-stroke engine retrofit packages for ammonia have yet to be formulated in technology concept, although initial interest has been confirmed in isolated vessel segments. The first ammonia-fuelled two-stroke test engine is in development, with several open questions around injection, combustion and emissions profile as well as safety and maintenance concept. This very immature state puts two-stroke ammonia retrofit technology at **TRL 3.**

For more detailed description of the state of engine retrofit technology readiness, see **Section 5.**

Fuel handling and storage

Fuel handling and storage technology includes the wider on-vessel fuel system around the engine, including fuel tanks, fuel preparation (including fuel pumps, fuel valve trains, heat exchangers and filters), emissions abatement technologies and safety equipment such as purging systems and vents.

The TRLs assigned below reflect the maturity of these technologies for both newbuild and retrofit applications, as the only difference is when the technologies are integrated – during initial construction or once the vessel has entered service. However, due to the constraints of converting existing vessels, not all newbuild technologies may be suitable for use in a retrofit (see **Section 6** for more detail on system integration).

Technology	TRL
Methanol fuel handling and storage	5
Ammonia fuel handling and storage	3

Methanol fuel handling and storage technologies have already been deployed on both ferry/ro-ro and methanol tanker vessels. The maritime industry has long experience of handling methanol as a cargo, meaning that containment, piping and safe handling are already well understood. Tank solutions and fuel supply systems are established and available from multiple suppliers. Emissions characteristics are known and manageable using existing technology. Enhanced safety measures for using methanol as fuel rather than cargo – for example venting, ventilation and fire control measures – have been deployed. These technologies have already been used in a retrofit case and will be used in others in the coming years, but a single retrofit prototype to date puts them at **TRL 5.**

Ammonia fuel handling and storage is at an earlier stage of development than methanol technology. While storage and piping are known from decades of handling ammonia cargoes and refrigeration systems, handling as a fuel is largely untested. Some solutions needed as part of an ammonia fuel system are only in early design stage. One example is the ammonia release and mitigation system, which prevents harm to crew and environmental damage by collecting ammonia from piping, valves and engine during purging, draining and other operations. Bilge systems capable of safely handling ammonia-contaminated water have also yet to be developed, as have arrangements for disposal of the contaminated water.

In some cases, the lack of regulatory guidance, for example on venting and requirements, is also slowing development of solutions. Requirements for emissions abatement also depend on greater understanding of combustion performance, which will only come as engine testing advances. Significant development work remaining places ammonia fuel handling and storage at **TRL 3.**

Investment & community readiness

Technology readiness is just one element of a solution being ready to be applied. The industry's willingness to adopt a technology is also based on its **investment readiness,** which signifies whether the business case is hypothetical or well proven. **Community readiness** is also crucial. This identifies whether the frameworks for safe and publicly acceptable use of a technology and fuel are in place for ships, ports and other affected communities.

Using the same evidence-based approach used for determining TRLs, LR followed a process established by its Maritime Decarbonisation Hub (MDH) for the **Zero Carbon Fuel Monitor** to determine the Investment Readiness Level (IRL) of methanol and ammonia retrofits in four separate vessel segments:

- Container ships
- Cruise vessels
- Bulk carriers
- Tankers

The IRLs can be found in **Section 9**, along with techno-economic analysis of the retrofit case for sample vessel types.

LR used the same process to determine a Community Readiness Level (CRL) for methanol and ammonia retrofits. This indicates the maturity of safety frameworks and public acceptance. This can be found in Section 4, alongside technical and compliance considerations for alternative fuel retrofits.

2 Regulatory drivers

Regulatory efforts targeting decarbonisation are driving demand for fuel retrofits by placing targets on emissions reduction, introducing market-based measures and stimulating fuel availability.

The pace at which the global shipping fleet takes up new fuels will depend on both regulatory requirements and investments in fuel availability. While the widespread availability of net-zero carbon ship fuels remains in the early development phase (see Section 3), the regulatory architecture that will drive decarbonisation is already emerging.

The societal will to decarbonise is enshrined in the global ambition to meet the Paris Agreement objective of limiting climate change to less than 1.5°C above pre-industrial temperatures. International shipping is not directly included in the agreement. This exclusion recognises the difficulty of apportioning ship emissions between countries, as well as the complexities faced by the International Maritime Organization (IMO) in setting the global framework for maritime emissions reduction.

IMO ambition and targets

IMO adopted its revised GHG reduction strategy as Resolution MEPC.376(80) the 2023 IMO Strategy on Reduction of GHG Emissions from Ships in July 2023. Key elements of the strategy include:

- To peak GHG emissions as soon as possible and to reach net-zero by or around, i.e., close to 2050, mindful of different national circumstances.
- To reduce GHG emissions on a well-to-wake basis, as addressed in the LCA Guidelines.
- To reduce GHG emissions within the boundaries of the energy system of international shipping and prevent a shift of emissions to other sectors.
- A reduction in CO_2 emissions per transport work (carbon intensity) by 2030 to be at least 40% as an average across international shipping compared to 2008 levels.
- Indicative checkpoints to reach net-zero GHG emissions from international shipping of 20% striving for 30% by 2030, and 70% striving for 80% by 2040, compared to 2008.
- Uptake of zero or near-zero GHG emission technologies, fuels and/or energy sources to represent at least 5%, striving for 10%, of the energy used by international shipping by 2030.

Short-term measures and intermediate targets will set the pace of change and influence decisions on fuel choices for both new and existing vessels. The current measures – namely the Energy Efficiency Design Index (EEDI), the Energy Efficiency Design Index for Existing Ships (EEXI), and the Carbon Intensity Indicator (CII) – are already encouraging ship owners to consider how to enhance their existing fleets and build efficiency into newbuilds.

Any new intermediate targets will need to be supported with more stringent CII, EEXI and EEDI requirements, or perhaps with new measures aimed more specifically at driving zero or near-zero carbon fuel uptake. For shipowners, understanding their requirements at each step will be critical for deciding preferred compliance options across the lifecycle of their vessels.

Lifecycle analysis guidelines

IMO outcomes will also affect which fuels can help them comply with emissions reduction requirements. IMO also approved resolution MEPC.376(80) the Guidelines on lifecycle GHG Intensity of marine fuels at MEPC 80 in July 2023. The well-to-wake and tank-to-wake emissions factors attributed to each fuel in the guidelines are intended to be used in future IMO measures to reduce shipping emissions.

The fuel type, feedstock, conversion process and other sustainability criteria associated with each specific batch of fuel will feed into compliance with any new IMO measure. This data will be displayed in some form in the bunker delivery note via a new Fuel Lifecycle Label designed to be compatible with IMO's Data Collection System (DCS), with the aim of requiring owners to report the information as part of its annual DCS filing.

Market-based measures

Given the high cost of net-zero fuels compared to conventional ship fuels, a key role of regulation is to make new fuels more cost competitive. This can be achieved by both encouraging the scale up of new fuel production and distribution to reduce their cost, and by placing restrictions or levies on fossil fuels to make them more expensive. IMO's ambition levels and future measures to regulate emissions may act as a signal to spur investment in marine fuels, but it has yet to adopt any market-based measures that would deter owners from buying fossil fuels.

The European Union has introduced both demand- and supply-side measures, through its Emissions Trading Scheme (ETS) and FuelEU Maritime Regulation. Passenger and cargo vessels of over 5,000GT sailing to, from or between EU ports will be included in the ETS, which starts in 2024. Under a two-year phase-in period, owners or operators will be required to pay for 40%, then 70% of their voyage emissions, or half of that if vessels are arriving from or departing to a non-EU port. Some smaller vessels could be included from 2027.

The EU ETS could quickly make low-carbon fuels more attractive. In February 2023 the ETS carbon price breached €100 per tonne of CO_2 equivalents for the first time, adding more than €300 to the cost of a tonne of HFO.

The FuelEU Maritime Regulation imposes a direct requirement on vessels to limit the greenhouse gas intensity of energy used onboard. It is applied similarly to the ETS, covering 100% of an intra-EU voyages or 50% if travelling to or from a non-EU port, and all energy used at berth in an EU port. The requirement for carbon intensity reduction of fuels used scales from 2% in 2025 to 6% in 2030, and then to 80% in five-yearly increments by 2050. From 2030 EU TEN-T maritime ports (meeting requirements of EU 2023/1804), and from 2035 all EU ports, are to provide an OPS connection for all electrical power demand of container and passenger vessels at berth.

In addition the UK and US are contemplating their own market based measures. The UK is consulting upon a scheme that would introduce an ETS for domestic voyages – those emissions from voyages between one UK port and another, or within a port, or at berth - for vessels of 5,000GT and over. This is planned for 2026. By keeping its application to domestic voyages, it avoids double counting with the EU scheme.

The US has two proposals for consideration, a Bill for a Clean Shipping Act which is broadly similar to FuelEU Maritime, and a Bill for an International Maritime Pollution Accountability Act, which is broadly similar to the EU ETS. Both are intended to commence in 2024, although neither has yet been passed and may take longer than to do so, if at all.

Harmonising regulatory regimes

The EU regimes mean that a considerable proportion of global shipping will be subject to market-based measures from 2024 and will need to decarbonise at a faster pace than demanded by current IMO legislation. The EU has committed to update its requirements if IMO measures, when introduced, are in line with its own objectives.

But the EU is not the only region to be considering an ETS or a fuel carbon intensity requirement. In the UK, for example, the Department of Transport's Clean Maritime Plan envisions a trading scheme and has already announced a UK Monitoring, Reporting and Verification requirement as a first step. The challenge for regulators, and potentially for ship owners, will be to ensure that emerging regimes do not overlap, contradict or add to the burden of complying with a global framework.

EU carbon pricing and the retrofit case

Analysis from LR highlights how EU's carbon pricing initiatives, the Emissions Trading Scheme (ETS) and FuelEU Maritime, could drive ship owners and operators to adopt alternative fuels.

From 2024, carbon dioxide (CO_2) emissions from ships ≥5000GT in 2024 reported under the EU's Monitoring, Reporting and Verification (MRV) system will also be included in the regional ETS. Those vessels in scope of the ETS will need to buy EU Allowances (EUA) to cover half of their greenhouse gas (GHG) emissions to and from EU, Norwegian and Icelandic (EEA) ports, and all emissions for intra-EEA voyages and while at berth at EEA ports. In 2025, 40% of the CO_2 emissions from voyages and at berth stays in 2024 will be subject to the ETS, ramping up to 100% in 2027. Just as the ETS phase-in ends there is a financial double-hit for shipowners. In 2026, the MRV will also require the reporting of CH4 (Methane) and N2O (Nitrous Oxide) emissions from ships, with EUAs to be paid on 100% of the CO_2 equivalent of those emissions, in addition to CO_2, within the ETS from 2027.

The other mechanism is FuelEU Maritime, which will come into effect in 2025. The regulation sets targets for reducing the yearly average GHG intensity of the energy used by a ship (or, crucially, by a fleet or pool of ships). The required GHG intensity reduction starts small, at -2% in 2025 (compared to a 2020 baseline), reaching -6% in 2030 and -14.5% in 2035, through to -80% by 2050.

A penalty or reward is then calculated based on the extent of under or over performance against the vessel or fleet's target for the year, and the cost of low-carbon fuel that would have been needed to meet the target.

For a large handy bulk carrier emitting 9,725 tonnes of CO_2 equivalents (CO_2e) on voyages to and from the EU, and 1,399 CO_2e tonnes on intra-EU voyages or at berth in EU ports, the cost of EUAs in 2026 would be €0.58 million, while the FuelEU Maritime penalty would be €0.20 million if the ship keeps using the same fossil fuel. But by 2035, the FuelEU Maritime penalty would be €0.71 million, while the EUA price would stay similar assuming the carbon market is stable. Looking to 2050, the FuelEU Maritime penalty reaches €3.60 million, six times the EUA spend needed to cover emissions.

These additional costs are likely to drive owners to consider whether switching to alternative fuels is a more cost-effective option. The EU rules offer the potential to offset an entire fleet penalties with just a few over-performing vessels. For example, a fleet of ten boxships could avoid around €277 million in FuelEU Maritime penalties in five years (2030-2034) if they are joined by a single vessel fuelled with e-methanol. That saving far outweighs the likely cost of building or retrofitting the methanol-fuelled containership.

VLSFO 19K TEU Boxship Fleet
wait & see scenario

x10

2030: **3.8 mil.€ x 10** **= 38 mil.€**
2031: **3.8 mil.€ x 10** x 1.1 **= 42 mil.€**
2032: **3.8 mil.€ x 10** x 1.2 **= 45 mil.€**
2033: **3.8 mil.€ x 10** x 1.3 **= 49 mil.€**
2034: **3.8 mil.€ x 10** x 1.4 **= 52 mil.€**

Council of EU proposed a multiplier of:

1 + (n -1)/10

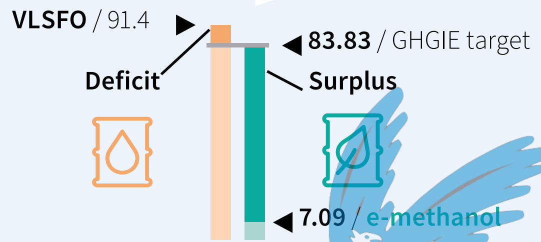
Where **n** is the number of consecutive reporting periods for which the company is subject to a remedial penalty for this ship

e-methanol Transition
green fuel scenario

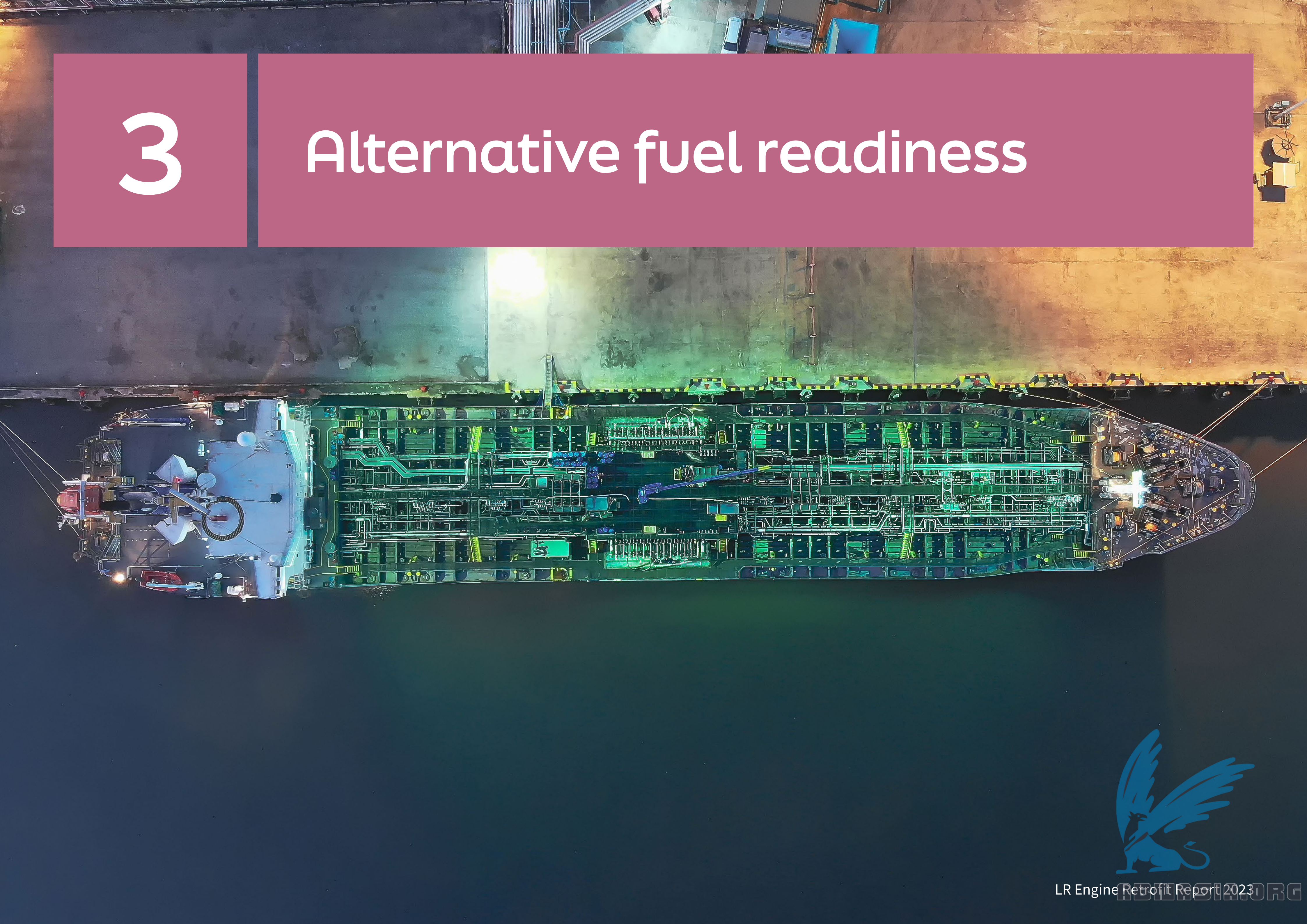
x10 + x1

2030 | 2031 | 2032 | 2033 | 2034

one ship running on e-methanol will create enough **surpluses** to balance **deficits** of ten VLSFO ships in the same pool every year **= €0**



3 Alternative fuel readiness



Forecasting where alternative fuels will be available and at what price will be crucial inputs to shipowner decisions on how and when to convert existing vessels.

If the 'why' of alternative fuel use is well understood, the 'how' remains far from clear. Ship operators have always used fuel cost projections in determining the business case for newbuildings and conversions. When many of the potential fuel options have yet to emerge at commercial scale, the uncertainty of such projections is even greater.

This uncertainty is one reason for anticipating a growing market for alternative fuel retrofits. The potential to convert vessels offers owners the flexibility to continue fleet development using established fuel options, with the potential to switch to other fuels when the case for their use can be established. But understanding when retrofitting will become viable still depends on understanding fuel cost and availability, often from a very specific local basis.

Lloyd's Register has established two useful tools for addressing these uncertainties. The Zero-Carbon Fuel Monitor assesses the readiness of fuels for maritime use in general, while with the First Movers Framework these options can be narrowed down for particular trades.

Zero-Carbon Fuel Monitor

The Zero-Carbon Fuel Monitor is an evidence-based framework developed by LR's Maritime Decarbonisation Hub to assess the readiness of the most promising zero-carbon fuels and related technologies that could play a role in getting the entire shipping industry to zero emissions by 2050. It is a resource for the industry showing the current state of developments and indicating progress towards industry-wide solutions. Zero-Carbon Fuel Monitor addresses three fundamental questions for decarbonising the global fleet:

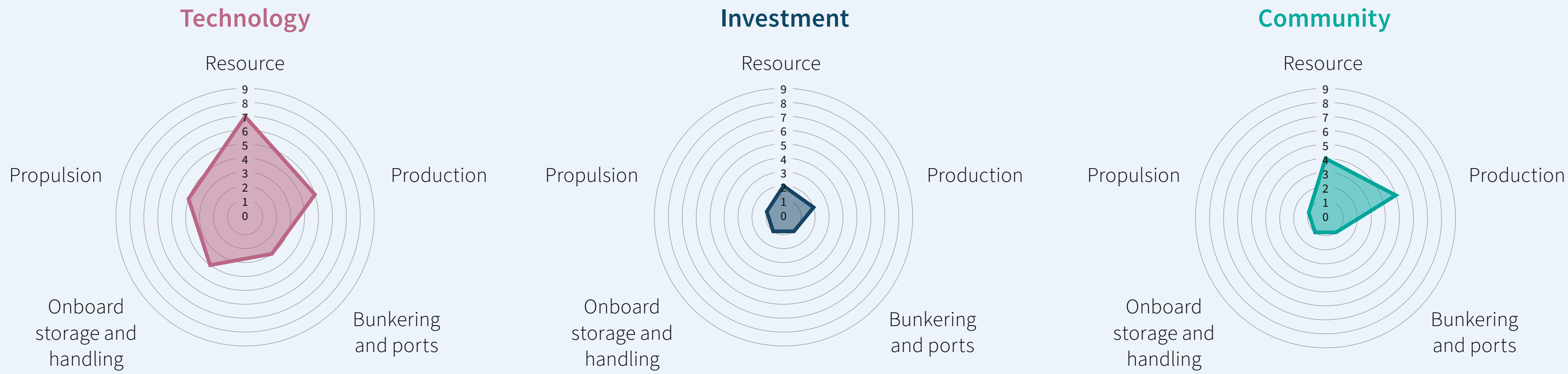
- How close is the fuel, and technology for its use, to being proven, scalable and safe?
- Is the business case robust enough to attract investment?
- How prepared are people and organisations to adopt the new solution?

The framework is structured into five main supply chain stages across the lifetime of a fuel, from natural resources through to vessel propulsion. For each stage, Lloyd's Register experts rate fuel for technology, investment and community readiness levels – TRL, IRL and CRL respectively - based on currently available evidence.

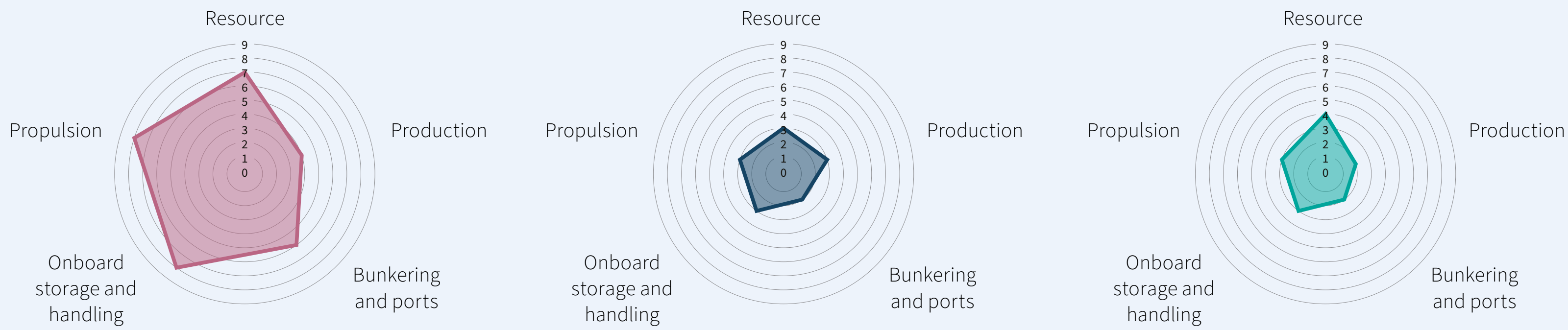
The Zero-Carbon Fuel Monitor is regularly updated based on new evidence. The latest readiness levels can be viewed as an online dashboard, including the rationale and evidence behind the readiness ratings, that can be found on LR's Zero Carbon Fuel Monitor lr.org/ZCFM. The following charts show the current summaries of TRL, IRL and CRL for renewable ammonia, methanol and methane.

Zero-Carbon Fuel Monitor

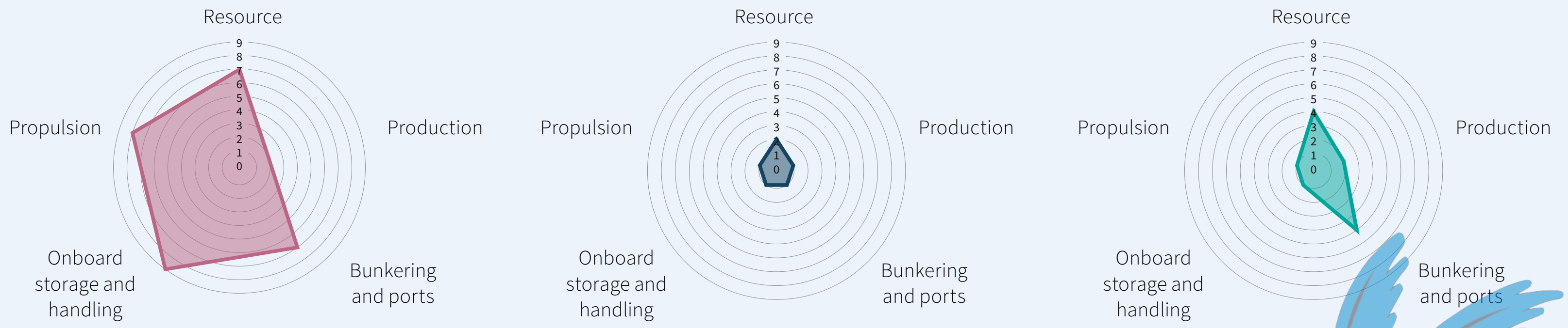
Ammonia TRL, IRL and CRL summary



Methanol TRL, IRL, CRL summary



Methane TRL, IRL, CRL summary



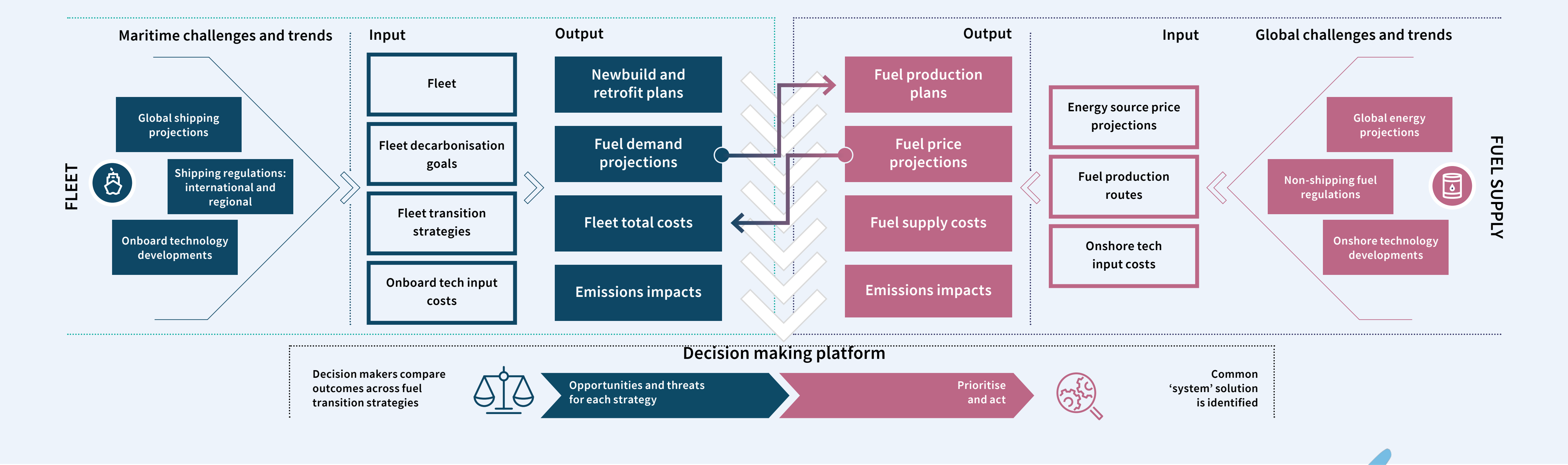
Explore readiness levels: Technology Readiness Levels (1-9) Investment and Community Readiness Levels (1-6)
Note: Lloyd's Register Zero-Carbon Fuel Monitor Dashboard, updated June 2023.
Zero carbon fuels are defined as energy systems that have the potential to deliver ship power with net-zero carbon dioxide emissions, inclusive of production and use.

First Movers Framework

While understanding the readiness of fuels is an essential element to considering future options, it can only be a starting point. In a recent project[1], The Lloyd's Register Maritime Decarbonisation Hub set out to establish an analysis which would not only highlight transition options but also show more clearly potential costs, risks and opportunities, as well as the steps and further considerations needed to reach an end decarbonisation goal.

To do this, experts had to consider not only the transition of the fuel supply, but also the transition of the fleet to which the fuels would be applied. The figure below illustrates how these two elements influence each other, with fleet fuel demand forecasts helping to justify fuel production plans, and fuel price projections helping to model fleet costs. The combined analysis, termed the First Movers Framework, can be used as a tool for collaboration between shipping and marine fuel stakeholders to identify pathways to decarbonisation for specific fleets.

First Movers Framework – fleet and fuel supply analysis

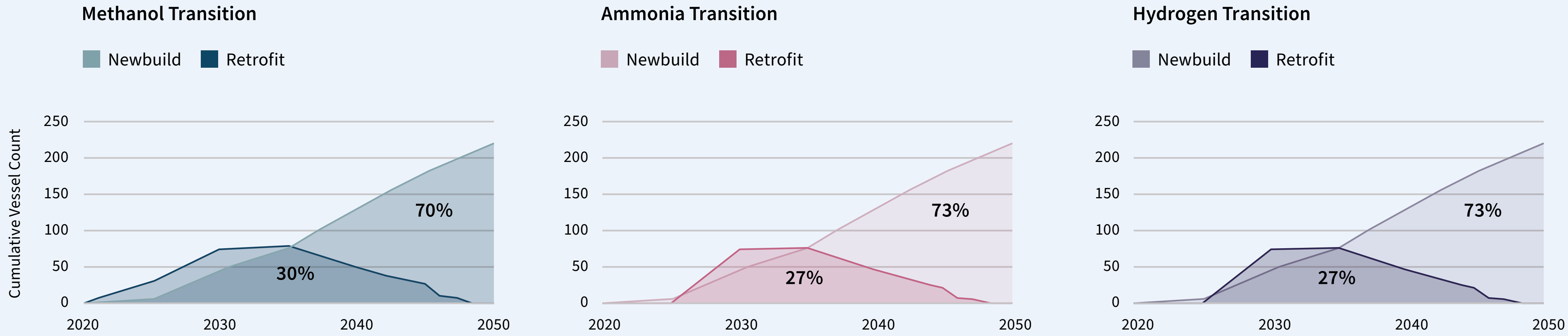


(1) First Movers in Shipping's Decarbonisation, Lloyd's Register, December 2021: https://www.lr.org/en/marine-shipping/maritime-decarbonisation-hub/about/our-story/research-library/first-movers-in-shippings-decarbonisation/

Applied to the fleet of container feeders operating between Singapore and Hong Kong, the analysis showed that transitions based on methanol, ammonia or hydrogen could achieve similar emissions reductions, but with very different infrastructures and at different costs. Up to 2050, total fleet costs are lowest for the ammonia transition ($44.5 bn), followed by methanol ($51.5 bn) and then hydrogen ($69.4 bn).

Importantly for the current study, the First Movers Framework analysis of the East Asian container feeder fleet identified that, in all fuel scenarios, approximately 26% of the transition (by number of ships up to 2050) is achieved through retrofitting. While the case study is for a specific fleet, the high demand for retrofits in each scenario indicates that converting vessels for alternative fuels will play a crucial role in a successful transition regardless of the fuels selected.

First Movers Framework Case Study – East Asian container feeder fleet newbuild and retrofit share by transition scenario



Lessons from LNG

Retrofit solutions for converting merchant vessels to use liquefied natural gas (LNG) have existed for nearly a decade, since Nakilat's LNG carrier Rasheeda had its main MAN engines adapted in 2015. Since then, uptake of LNG has grown rapidly, while retrofits have remained uncommon. Looking at some of the factors around LNG retrofitting is valuable for identifying issues that are also relevant to conversions for other fuels.

Fuel cost

One reason why LNG retrofits are relatively rare today is the rising cost of the fuel compared to fuel oil. With many newbuild dual-fuelled vessels choosing to operate on VLSFO while gas prices are high, there is little business case for converting to dual-fuel LNG engines only to be forced into diesel operation. Adopters of other alternative fuels will also face cost hurdles, as even with significant carbon pricing these fuels are unlikely to be competitive with fuel oil, either in price or availability, in the next few years.

Emissions profile

Another reason for the low market interest in LNG retrofits is the fuel's emissions profile. LNG was originally adopted as a marine fuel to meet sulphur emissions limits and also offers NOx Tier III compliance without aftertreatment for certain engine types. When it comes to greenhouse gases, LNG offers reduced tank-to-wake emissions of CO_2 (up to 23% compared to fuel oil). This taken alone is a significant step towards intermediate decarbonisation targets, albeit relatively small compared to green methanol or zero-carbon green ammonia.

However, the future availability of LNG as an e-fuel or derived from biomass could provide a net-zero or near-zero carbon equivalent that could be used in existing LNG engines.

The biggest emissions challenge for LNG is methane, a potent greenhouse gas that is emitted at many stages of the LNG fuel supply chain, from production to use in engines. Though relatively low compared to CO_2 emissions, fugitive methane has an outsized impact; it contributes 80 times more than CO_2 to global warming per tonne over a 20-year time frame, and 28 times more across a hundred-year span. While methane emissions from ships are not yet regulated, they will be included in future IMO regulation with the Guidelines on lifecycle GHG intensity of marine fuels. As such, methane slip from ship engines casts doubts on the GHG emissions reduction impact, as CO_2e including CO_2, CH_4 and N_2O, of LNG fuel.

Initiatives are underway to minimise methane emissions from both upstream production and downstream use. High-pressure injection engines already offer very low methane slip, while OEMs of low-pressure injection engines are working to optimise combustion to reduce unburned methane, as well as considering new methane abatement technologies including catalytic reduction.

One important industry project to maximise the greenhouse gas reduction potential of LNG fuel is the **Methane Abatement in Maritime Innovation Initiative (MAMII)**, established in 2022 by Lloyd's Register's Safetytech Accelerator. Supported by several ship operators and fuel suppliers (including Maran Gas Maritime, MSC, Carnival Corporation, Seaspan, Shell and Knutsen Group), the project aims to propose novel methane reduction methods to industry, drawing on the expertise of academics, civil society, and other stakeholders including the UK's National Physical Laboratory.

The methane slip issue highlights the need for technology developers and potential users of alternative fuels to consider the full range of greenhouse gas contributors. In the case of ammonia for example, N2O is one potential new emission source. Even hydrogen when released unburned contributes to global warming.

Retrofit challenges

Installing LNG fuel systems on existing merchant vessels has proven to be not straightforward, as illustrated by the case of the first retrofit on a large container vessel, Hapag-Lloyd's Brussels Express (formerly Sajir). The project was carried out on a vessel that had already been classed as 'LNG-ready' but took around nine months to complete at an estimated cost of US$35 million – highlighting that class 'ready' recognitions such as notations or descriptive notes, should not in isolation be taken to indicate that a conversion will be simple; it depends on the scope and level of the recognition.

The retrofit cost and time off-hire are considerable obstacles to all alternative fuel retrofits, as are the space requirements for fuel systems. On Sajir, the equivalent of 350 TEU was lost to install LNG tanks and pipework. For fuels like methanol and ammonia, which require even more tank volume than LNG, careful design will be needed to avoid even greater sacrifices in cargo capacity.

Since Sajir there has been development in fuel system design and integration capability, with the potential to dramatically reduce installation time and cargo compromises. However, partly due to the challenges of the high-profile project as well as other market dynamics, few poster cases have emerged for the viable retrofitting of large merchant vessels.

Regulation, safety and training

An early hinderance to the uptake of LNG was the lack of a regulatory framework both on ships and ashore. IMO's IGF Code was initially developed to accommodate the use of LNG as fuel beyond gas carriers. Today that framework is being extended as other low-flashpoint or gas fuels are considered for marine use. The code now includes interim guidelines for methyl and ethyl acohol and LPG while ammonia and hydrogen rules are under development.

As LNG use has increased, formal frameworks for crew training and safe handling while bunkering in port have emerged across the world. These frameworks, which provide guidance for handling a cryogenic, pressurised, low flashpoint, gaseous fuel, can also be used as a starting point from which regulators including port authorities can develop rules around other alternative fuels.

A case for LPG

Liquefied petroleum gas (LPG), consisting of propane and butane mixes, is a niche marine fuel that is increasingly used by vessels that carry the fuel, which can include dedicated LPG carriers or ethane carriers. It also has similarities with ammonia in regard to engine fuel systems, with MAN Energy Solutions initiating its ammonia engine development from the base of its existing ME-LGIP engine, which runs on LPG and has already been successfully retrofitted.

While LPG offers limited advantages over fuel oil in terms of GHG emissions, advances have recently been made in the production of biomass and electricity derived equivalents, which could result in near-zero carbon fuels. Carbon capture is a potential avenue for reducing the greenhouse gas emissions from fossil LPG and, given similarities to ammonia when used as fuel, a retrofit pathway from LPG to zero-carbon ammonia could also be explored. The benefits for ship operators of using LPG would include its relatively stable low price and its wide availability.

Lloyd's Register is a member of the World LPG Association (WLPGA) and chairs its Marine Working Group. Together with WLPGA, Lloyd's Register is developing a guide to using LPG as a marine fuel, supported by a feasibility study for a retrofit case of an LPG dual-fuel main engine onboard a container ship in service. The initiative aims to further inform stakeholders on the opportunities of LPG as a marine fuel, highlighting its characteristics, while exploring environmental sustainability and commercial potential.

4 Technology and compliance considerations

The rules to which alternatively fuelled vessels are designed, certified and classed are in various stages of development, with particular challenges for owners considering fuel conversions.

The ship design and systems needed to use methanol and ammonia as fuel are regulated by IMO under both safety (SOLAS) and environmental (MARPOL) conventions. Section 6 details the systems involved and how they can be integrated in vessel conversions. This section provides an overview of the status of regulations governing use of methanol and ammonia, as well as areas that will require particular consideration for vessel retrofits.

At present, operators planning both newbuild and retrofitted ships using these fuels must follow an 'alternative design' approach, based on risk assessments and approval by flag and class. More well-established rules will eventually improve the ease and cost of designing these vessels.

While IMO statutory instruments and class rulesets are under development, Lloyd's Register has issued full rules and guidance for vessels using methanol, ammonia and hydrogen, and applies the established ShipRight Risk Based Certification (RBC) process.

A joint study into ammonia safety onboard ships undertaken by the Lloyd's Register (LR) Maritime Decarbonisation Hub and the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) provides recommendations for design and operation of ammonia-fuelled vessels. (Reference to report.) The study identifies a range of mitigation methods, from ship design to crew training and operations, that are required to keep toxicity risks to crew within published tolerable limits.

For fuel conversions, key design challenges include demonstrating two key factors:

- Ensuring that the system and all sub systems meet the goals and functional requirements of the IGF Code.
- Meeting the NOx recertification requirements for engines retrofitted for new fuels.

SOLAS requirements

IGF Code

The IMO requirements for vessels using methanol and ammonia fall under the mandatory International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code[5]).

While the IGF Code currently contains detailed requirements for the use of only natural gas as fuel it does contain goals and corresponding functional requirements, as well as training requirements, which are generic to all gaseous and low flashpoint fuels. The detailed prescriptive requirements under Part A-1 of the IGF Code have been developed to meet these goals and functional requirements for natural gas (methane).

To use gases or low-flashpoint fuels other than methane, the alternative design provisions from Part A, 2.3 of the IGF Code need to be applied, requiring an engineering analysis to be submitted to the Flag administration, in accordance with SOLAS regulation II-1/55 and associated guidelines[6]. This process follows a risk-based approach for approval of the design to ensure the goals and functional requirements of the IGF Code have been met.

In the case of methanol, ammonia or ethanol, IMO's MSC.1/Circ.1621 interim guidelines (see below) follow the IGF Code format and include detailed prescriptive requirements for methanol that meet the IGF Code goals and functional requirements.

For all vessels projects using alternative fuels, a key question under the IGF Code is how the design will meet the functional requirements of IGF 3.2 where IMO has not published prescriptive requirements such as those in Part A-1 of the IGF Code and MSC.1/Circ.1621.

IGF Code functional requirements for all fuels

Part A	Functional requirement
3.2.1	The safety, reliability and dependability of the systems shall be equivalent to that achieved with new and comparable conventional oil-fuelled main and auxiliary machinery.
3.2.2	The probability and consequences of fuel-related hazards shall be limited to a minimum through arrangement and system design, such as ventilation, detection and safety actions. In the event of gas leakage or failure of the risk reducing measures, necessary safety actions shall be initiated.
3.2.3	The design philosophy shall ensure that risk reducing measures and safety actions for the gas fuel installation do not lead to an unacceptable loss of power.

For newbuild projects and also for retrofits - where new machinery, fuel processing and storage, piping and safety measures must be tailored to an individual vessel's layout - proving these functional requirements are met demands a rigorous design assessment process.

Interim methanol guidelines

In November 2020, IMO's Maritime Safety Committee approved the 'Interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel' as MSC.1/Circ.1621 under the framework of the IGF Code[7]. These guidelines are planned to be incorporated into the IGF Code at a later date . These guidelines follow the format of the IGF Code structure with goals and functional requirements specific to methyl/ ethyl alcohol fuels and detailed prescriptive requirements that meet those goals and functional requirements. The guidelines also require a risk assessment to be undertaken.

IGC Code

The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) includes provision for burning methane and other non-toxic cargoes as fuel, but does not specifically govern gas-fuelled ships. In the absence of IMO legislation for ammonia-fuelled vessels, IGC requirements around fuel tanks, materials and safety precautions around ammonia are useful for assisting ammonia-fuelled ship design. These include:

- **Personnel protection (14.4):** Self-contained breathing apparatus and gas-tight protective clothing for all onboard personnel; decontamination shower facilities.
- **Material compatibility (17.2.1):** Materials to be resistant to the corrosive action of gases and materials such as mercury, copper and copper-bearing alloys, and zinc not to be used for construction of cargo tanks and associated pipelines, valves, fittings and other items of equipment normally in direct contact with the cargo liquid or vapour.
- **Stress Corrosion Cracking (17.12):** Requirements to minimise the risk of stress corrosion cracking in containment and process systems made of carbon-manganese steel or nickel steel.

The IGC Code (Chapter 16 Use of Cargo as Fuel) rather than IGF Code applies to liquefied gas carriers using their cargo as fuel under the 'one ship, one code' amendments to SOLAS II-1 made with the adoption of the IGF Code. However the IGC Code, Chapter 16.9.2 prohibits the consumption of toxic cargoes, including ammonia, as fuel. Current proposals to amend the clause could be approved by December 2024 at the earliest.

MARPOL requirements

NOx recertification

For retrofits in particular, the IMO NOx Technical Code 2008 is an important consideration. Through MARPOL Annex VI Regulation 13, a dual fuel retrofit would count as a 'substantial modification', requiring that the engine maintains the NOx emission tier level determined by the date of the vessel's original keel laying date.

A retrofitted engine would likely have NOx critical components changed, this means that the retrofitted engine would need to be recertified and the NOx Technical File updated. Unless a matching engine with the same components exists and has already been NOx certified, which could form a basis for recertifying the retrofitted engine, recertification would require either a test on an identical engine on the testbed or testing once retrofitted.

Particularly in the early stages of alternative fuel conversions, NOx recertification requirements pose a challenge to ship designers that can significantly add to the cost of a retrofit project. If no matching engine has previously been tested, the cost involved in sourcing and modifying an engine to match, and test could be high. Testing a modified engine in situ necessitates considerable disruption to operations as the engine needs to be operated at a steady state for long periods, which is unlikely to be compatible with a vessel's voyage plan.

Due to the requirement for NOx recertification only if there is no tested matching engine, this issue will become less of an obstacle as more retrofitted engines enter service. Meanwhile LR is collaborating with OEMs to formulate potential proposals to adapt the NOx certification requirements for retrofitted engines. These proposals will need to be adopted by IMO as amendments to the NOx Code.

Classification rules

The IGF Code is reflected in LR's Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels. The interim methyl and ethyl alcohol guidelines are reflected in LR's Requirements for Ships Using Methyl Alcohol (Methanol) or Ethyl Alcohol Appendix LR1 to those Rules. LR's rules for ships using ammonia as fuel are effective from July 2023, and LR has also published the industry's first rules for ships using hydrogen as fuel.

		Rules applicable	
Design/equipment area	**Rules goal**	**Methanol**	**Ammonia**
Ship Design and Arrangement	To provide for safe location, space arrangements and mechanical protection of power generation equipment:, fuel storage systems, fuel supply equipment and refuelling systems	LR LFP Appendix LR1 Part A-1, 5; otherwise Rules and Regulations for the Classification of Ships and the Rules and Regulations for the Construction and Classification of Ships for the Carriage of Liquid Chemicals in	LR LFP Appendix LR2, Part A-1, S; otherwise LR LFP Part A-1 and Part A-2
Fuel Containment System	To provide that gas storage/fuel containment is adequate so as to minimize the risk to personnel, the ship and the environment to a level that is equivalent: to a conventional oil fuelled ship	LR LFP Appendix LR1 Part-A-1, 6; otherwise Rules and Regulations for the Construction and Classification of Ships for the Carriage of Liquid Chemicals in Bulk	LR LFP Appendix LR2, Part A-1, 6; otherwise LR LFP Part A-1 6.3; Rules and Regulations for the Construction and Classification of Ships for the Carriage of Liquefied Gases, in Bulk Ch. 4 Part E, Ch. 4 Part A4 .5, Ch 6, Ch 17.12
Material and General Pipe Design	To ensure the safe handling of fuel, under all operating conditions, to minimize the risk to the ship, personnel and to the environment, having regard to the nature of the products involved	LR LFP Appendix LR1 Part A-1, 7; otherwise Rules and Regulations for the Classification of Ships, Pt 5, Ch 12; Rules and Regulations for the Construction and Classification of Ships for the Carriage of Liquid Chemicals in Bulk, Ch 5; Rules for the Manufacture, Testing and Certification of Materials	LR LFP Appendix LR2 Part A-1~ 7; otherwise LR LFP Part A-1 7.3; Rules and Regulations; Rules for the Manufacture Testing and Certification of Materials, July 2022. For the Classificat ion of Ships, Pt 5, Ch 12; Rules and Regulations for the Construction and Classification of Ships for the Carriage of Liquid Chemicals in Bulk, Ch 5, Ch 17.12
Bunkering	To provide for suitable systems on board the ship to ensure that bunkering can be conducted without causing danger to persons, the environment or the ship	LFP Appendix LR1 A-18;	LFP Appendix LR2 A-1 8 and LFP A-1 8.3, 8.4, 8.5; LFP B-1 16. 7
Supply to Consumers	To ensure safe and reliable distribution of fuel to the consumers	LFP Appendix LR1 A-19	LFP Appendix LR2 A-1 9; LFP A-19.3 9.9; Rules and Regulations for the Classification of Ships Pt S Ch 11
Power Generation Including Propulsion and Other Gas Consumers	To provide safe and reliable delivery of mechanical, electrical or thermal energy	LFP Appendix LR1 A-1 10; Rules and Regulations for the Classification of Ships Pt 5, Pt 6	LFP Appendix LR2 A-110; LFP A-1 10.3; Rules and Regulations for the Classification of Ships Pt 5

		Rules applicable	
Design/equipment area	**Rules goal**	**Methanol**	**Ammonia**
Fire Safety	To provide fire protection, detection and fighting for all systems related to storing, handling, transfer and use of methyl/ethyl alcohol as fuel	LFP Appendix LRl A-1 11; Rules and Regulations for the Classification of Ships, Pt 6	LFP Appendix LR2 Aa-111; LFP A-1 11,15
Explosion (and Toxic Injury) Prevention	To provide for the prevention of explosions and for the limitation of their effects, and (for ammonia) to provide for the prevention of toxic injury	LFP Appendix LR1 A-112; Rules and Regulations for the Classification of Ships, Pt 6	LFP Appendix LR2 A-111; LFP A-1 11. 7, 12.3-12.5, 15
Ventilation	To provide for the ventilation required for safe working conditions for personnel and the safe operation of machinery and equipment	LFP Appendix LR1 A-1 13	LFP Appendix LR2 A-113; LFP A-1 13.3-13.8, 15.8
Electrical Installations	To provide for electrical installations that minimizes the risk of ignition in the presence of a flammable atmosphere	LFP Appendix LR1 A-1 14; Rules and Regulations for the Classification of Ships, Pt 6	LFP Appendix LR2 A-1 A-14; LFP A-1 14.3
Control, Monitoring and Safety Systems	To provide for the arrangement of control, monitoring and safety systems that support an efficient: and safe operation of the fuel installations	LFP Appendix LR1 A-1 15; Rules and Regulations for the Classification of Ships Pt 5, Pt 6	LFP Appendix A-1 LR2; LFP A-1 9.3J 15.3-15. 10; Rules and Regulations For the Classification of Ships, Pt 6
Drills and Emergency Exercises	To ensure that seafarers on board ships to which these guidelines apply, are adequately qualified, trained and experienced	LFP Appendix LRl A-1 16,	Not drafted
Operation	To ensure that operational procedures for the loading, storage, operation, maintenance and inspection of systems for fuels minimize the risk to personnel, the ship and the environment and that are consistent with practices for a conventional oil fuelled ship whilst taking into account the nature of these fuels	LFP Appendix LR1 A-1 16	Not drafted

Risk Based Certification

To help owners navigate the certification process needed for both methanol and ammonia-fuelled vessels, LR uses the ShipRight Risk Based Certification (RBC) to demonstrate equivalence with SOLAS Alternative Designs and Arrangements (II-1 Reg. 55, II-2 Reg.17 and III, Reg. 38). The five-stage process is described in the 'Process for Risk Based Design' flow diagram below.

RBC-1: Design & Safety Statement

The output of RBC-1 needs to be a Design and Safety Statement Report prepared by the submitter and submitted to LR for appraisal. This report should identify stakeholders and their principal roles, describe the design and its intended use, list the rules and instruments under which the design is to be appraised, and provide an outline plan for RBC completion.

To assist in design understanding and development, there may be a requirement or a request for a Preliminary Appraisal of Rules (PAR, sometimes referred to as 'Design Screening'). Essentially, PAR is a screening of the design against applicable rules, instruments and goals.

RBC-2: Risk Assessment

The output of RBC-2 needs to be a written ToR and a Risk Assessment Study Report, both of which need to be documented by the Submitter and submitted to LR for appraisal.

RBC-3: Supporting studies

The actions documented in the Risk Assessment Study Report could require supporting studies, for example: to help address details that were unknown at RBC-2 stage or uncertainties in risk assessment inputs, to confirm the suitability of design options or changes, or to help inform construction and in-service requirements, inspection, testing and analysis requirements.

The output of each RBC-3 study needs to be a written ToR and a Supporting Study Report documented by the Submitter and submitted to LR for appraisal.

RBC-4: Final Design Assessment

The Final Design Assessment (RBC-4) needs to be a study of the 'completed' design that has been informed and revised by all RBC stages. Its purpose is to determine if further modification or refinement is required for 'acceptance' of the risks presented by the design, to summarise why the design should be accepted by LR and/or the regulator, and to provide input to design appraisal and third-party certification.

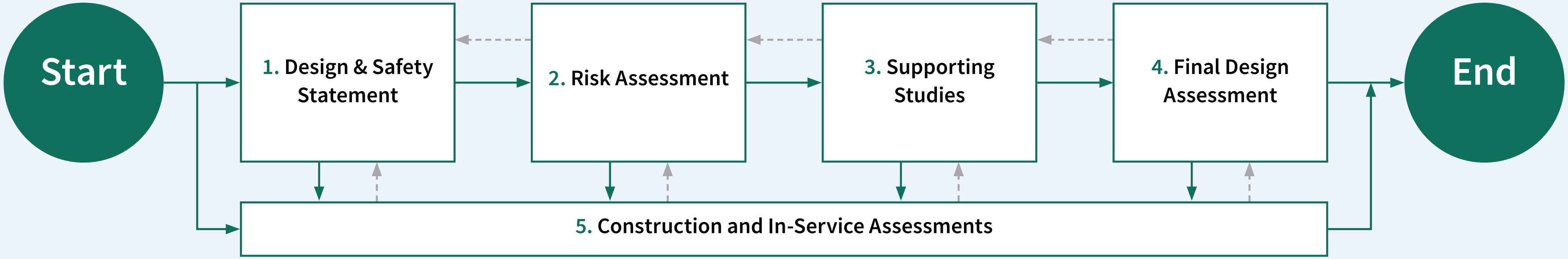
The output of RBC-4 needs to be a written ToR, a Final Design Assessment Study Report and all in-service documentation required in RBC-5, below.

RBC-5:

RBC-5a is a study of the requirements for construction, installation and commissioning of the design that has been informed and revised by the previous stages. The output of RBC-5a needs to be a written TOR and procedures for installation and commissioning, which need to be documented by the Submitter and submitted to LR for appraisal.

The purpose of RBC-5b is to develop and deliver the in-service documentation, including Operation Manuals, Maintenance Programme, Survey Requirements and through-life process for Change Management. The output of RBC-5b needs to be a written ToR and the in-service documentation, both of which need to be documented by the submitter and submitted to LR for appraisal.

Risk Based Certification (RBC) Process



Source: ShipRight Design & Construction, Risk Management, Risk Based Certification, September 2021

LR Gas Technology Specialist Sobhith Hariharan explains how the RBC process can be applied to a retrofitted ammonia-fuelled vessel.

“If you are adding ammonia as a fuel, you are adding a number of different components and elements to a standard design. So, the first exercise is to find out what these essential additional components are. And then by adding all these, what additional risks are you adding on to the vessel's design and operation? If you’re adding the risk, how do you manage that?”

This process is iterated until the safety criteria are satisfied. As the process continues and the design evolves, more granular risk assessments and HAZOP workshops focus on minimising each individual risk. Once all revisions and supporting studies have been completed, and mitigating measures have been shown to be effective, the final design assessment report is completed.

“This is essentially how we address all the risks,” says Hariharan. “It’s a very stringent process, but for the right reasons.”

5 Current engine retrofit technologies

Engine developers are ready to deploy the first methanol retrofit packages on a limited number of engine sizes, while ammonia conversions are likely to begin slowly from early 2027.

The ability to consume alternative fuels safely, efficiently and reliably in engines is the core technology requirement before vessel retrofits can be considered. In this respect, the projected availability of retrofits corresponds with the current status of marine engine development in general; engine concepts that can use methanol as fuel already exist – although they are not yet available from all engine developers - while concepts that use ammonia are still in the early development stages.

Retrofit package availability

When retrofit packages will be available in the specific sizes required for particular vessels depends on several factors. In the case of two-stroke engines, scaling for different engine sizes is not necessarily a straightforward or linear process, albeit the first engine deliveries prove the concept and ability to obtain the required approvals. This means that the roll out of alternative fuel capability across the full range of engine sizes typically follows actual engine orders.

Once engine concepts are established, retrofit packages can be developed to convert engines for use with new fuels. This design process usually takes six months or more. In the case of ammonia-fuelled engines, the additional safety requirements for both testing and operation may extend this timeframe, resulting in a slightly longer lag between newbuild and retrofit engines entering service. In the case of methanol, there are already newbuild engines in service and existing interest in conversion packages, meaning development could be relatively fast.

For four-stroke engines, retrofit technology can be installed even ahead of newbuild engines going into production. Both MAN and Wärtsilä are developing methanol capability first via retrofits, while Hyundai Himsen has undertaken type approval of its methanol-fuelled four-stroke engines as newbuilds. Unlike for two-strokes, four-stroke engines also offer the option of being retrofitted one after the other while the vessel is in operation, if sufficient generating power can be maintained. A shorter drydocking would still be needed for the wider fuel storage, fuel supply system, auxiliary equipment and safety systems.

Engine concepts and components

There are different combustion and fuel system approaches possible and required for the combustion of either methanol or ammonia compared to conventional fuels. Combustion concept, ignition principle, injection pressure and valve timing are some of the key parameters that will determine how effectively the fuel is burned. Aside from basic engine characteristics and air systems, one of the key design challenges are the fuel injectors that can operate at high pressures, and injection and valve control systems that are precise enough to manage the required pilot and main fuel injections and engine valve timing.

The two main combustion concepts applied for DF marine engines using gaseous or low-flashpoint fuels are the Diesel cycle, where the fuel is injected at high pressure into the compressed air in the cylinder, and the Otto cycle, where fuel is introduced (pre-mixed) into the air side in the charge air system at low-pressure during the induction and compression stages. In both cases the alternative fuel is then ignited with a small amount of pilot fuel oil.

In two-stroke engines, both main designers are opting for Diesel cycle combustion for methanol and ammonia, which maximises fuel efficiency and offers lower emissions – particularly a lower risk of fuel slip, an important safety consideration when dealing with toxic fuels.

Regulating the flow of fuel and air, together with control of auxiliary systems such as hydraulic oil for fuel injection equipment operation, sealing oil systems and nitrogen (to purge fuel lines) can all be critical elements in methanol and ammonia engines and accounts for a large part of the complexity around engine design. As well as nitrogen purging, segments of fuel lines also need to be isolatable – typically with master fuel valves and with double block and bleed valves – in order to switch quickly to diesel mode in the event of a leak from the gaseous or low-flashpoint fuel system, isolate that fuel system and reduce the inventory of the fuel leak. Double wall piping systems are typically used for the gaseous or low-flashpoint fuel supply with dilution air continuously circulated through the outer pipe of the double-walled piping, with gas detection of the ventilated air to detect any leak from the inner fuel pipe.

Managing these more precise and complex systems means that engine control system hardware and software will need to be adapted for methanol or ammonia engines. The alarm, monitoring and safety systems will also need to be enhanced to accommodate new safety measures.

Across the engine and fuel system, materials will need to be selected that are compatible with the specific fuel type that will be used. Ammonia is the more restrictive and requires typical construction materials and alloys such as copper, brass, zinc, and polymer components to be reselected.

Common viewpoints

While there are significant differences in how advanced each engine designer is with their methanol and ammonia fuelled engines, and in developing retrofit packages for them, there are several notable factors where all technology providers meet in agreement. Namely:

Methanol moving ahead: The technology obstacles to using methanol as fuel appear limited, with both two-stroke and four-stroke engines already in operation for some years, including some which have been retrofitted.

Ammonia safety gaps: Ammonia combustion research is continuing and options on concepts are emerging. A more challenging issue for engine developers is the safety aspects of ammonia. This presents itself both in gaps in regulation, with no IMO requirements in place yet and for example differing prescriptive rules for venting arrangements, and in operational aspects such as crew training and maintenance.

Integration challenges: Perhaps naturally, engine designers noted that the biggest obstacles for uptake were not related to the engine itself, but rather to the integration of fuel storage and handling and auxiliary systems into the existing vessel structure. Subsequent chapters in this report explore these challenges in more detail (Sections 6 and 7).

NOx emissions certification: All but one engine designer noted that the current requirements for certification of NOx performance is a likely impediment to uptake of retrofits, by increasing the overall project cost. The issue is explored in Section 2.

Pre-operational conversions: Two engine designers, Wärtsilä and WinGD, are involved in projects where engines will be converted for methanol fuel even before the original newbuild vessel is due to enter service. This trend highlights the pace of development in both engine technology and industry appetite for new fuel capability. As the business models around using methanol and ammonia mature, and with repair yard capacity and capability in such projects limited, it is possible that more 'pre-operational conversions' will take place in the coming years.

The following chapter highlights development towards methanol and ammonia engine retrofit packages from some key engine designers for both two-stroke and four-stroke engines.

Two-stroke engines

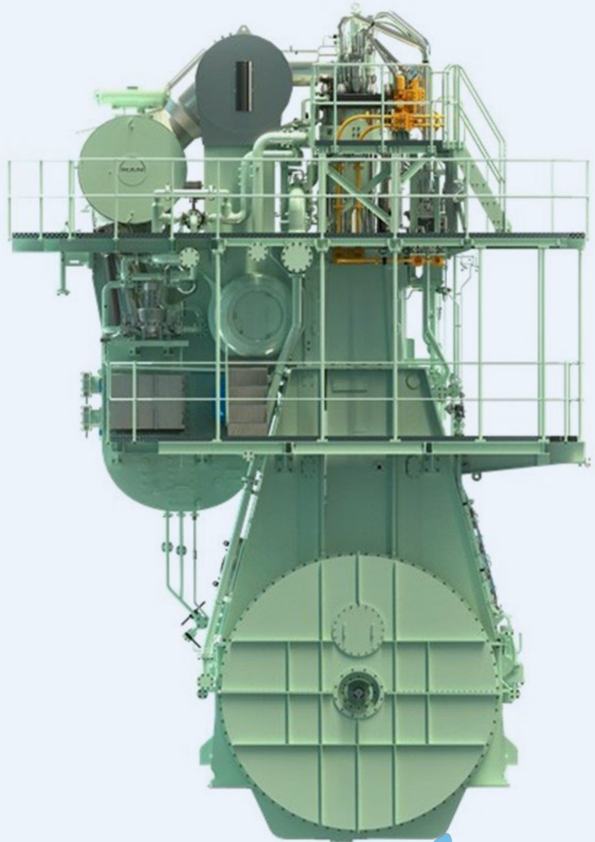
MAN Energy Solutions

Methanol

MAN Energy Solutions' first methanol-fuelled two-stroke engines entered service in 2016 onboard a series of methanol tankers owned by Marinvest and Waterfront Shipping, and today has 19 of the 50-bore engines in operation. They will be joined by around more than 100 engines on order across larger sizes, including 60-, 80- and 95-bore, for the first methanol-fuelled containerships.

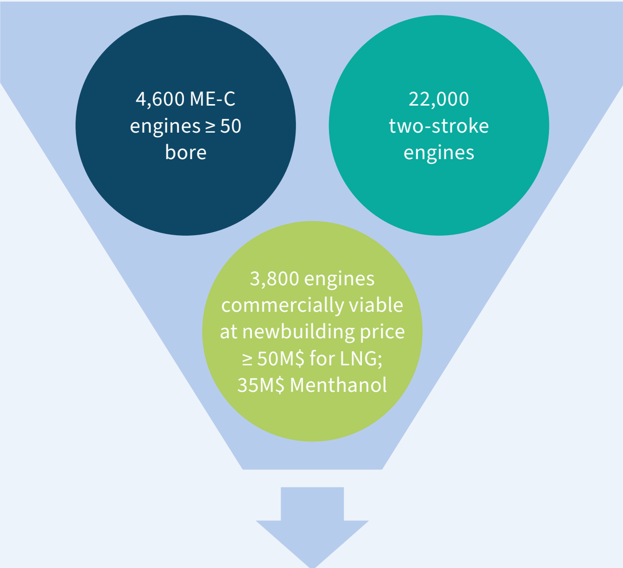
MAN Energy Solutions has already received orders from Maersk and Seaspan (for Hapag-Lloyd) for up to 80 retrofit packages in total on larger container vessels, and noted further interest from owners of methanol tankers and ro-ro vessels. The projects cover engine bore sizes including 95, 80 and 50. That equates to a market of more than 800 operating MAN engines that can already be retrofitted for methanol.

Retrofit projects in these engine sizes will begin next year and, with a project lead time of around 14 months for the first retrofits, MAN anticipates that many vessels will have been converted in 2025. In principle, a retrofit package can be developed for all electronically controlled engines – meaning most engines that have been delivered since their introduction in 2003. In practice, the business case for retrofits – which are likely to cost around US$12 million – means that only younger vessels of a relatively large size are viable candidates initially. The business case is expected to widen as technology, integration capability and fuel costs evolve.



MAN B&W ME-LGIM methanol-fuelled engine

Retrofit dual-fuel conversion market potential



2,500 engines with matching parent engine test in alternative fuel version

MAN evaluation of initial fuel conversion candidates

Main qualification parameters

- Engine type ME-C
- Engine size ≥ 50 bore
- Parent engine test available
- Sea trial after 1 Jan 2015
- Newbuilding price ≥50M$
- Total retrofit costs not to exceed 25% of newbuilding value

Typical qualified vessel types

- Tankers >50,000 DWT
- Bulkers >160,000 DWT
- Containers >7,000 TEU
- PCTC >6,000 CEU

Drivers

- GHG regulation
- ETS credits in a fleet perspective (pooled compliance)
- Customers in container market (B2C) are focused on lowering CO_2 emissions (market pull)
- B2C market for container carriers: relatively easy to pass on the cost to customer
- Issue with refunding of ships on fossil fuel: green funding schemes

Bottlenecks

- Fuel price/availability
- Certifications: Currently requirement for physical parent engine although new low carbon fuels consistently have lower NOx
- 10-15 shipyards to carry out conversions: engineering/ naval architect competences at repair yards are low
- Owners' ability to make solid retrofit budgets having repair yards as subcontractors - too high risk of budget overshoot
- Technical organization capacity of owners
- B2B market for bulkers and tankers: relatively difficult pass on the cost to customer

To support the development of a two-stroke fuel retrofit package, there needs to be either a similar newbuild engine in service using the same fuel, or exceptionally high market demand. This is in part due to the NOx recertification implications under MARPOL, which may require that after conversion the engine or an identical engine is tested at steady state either in service – a costly and often impractical exercise – or on a testbed.

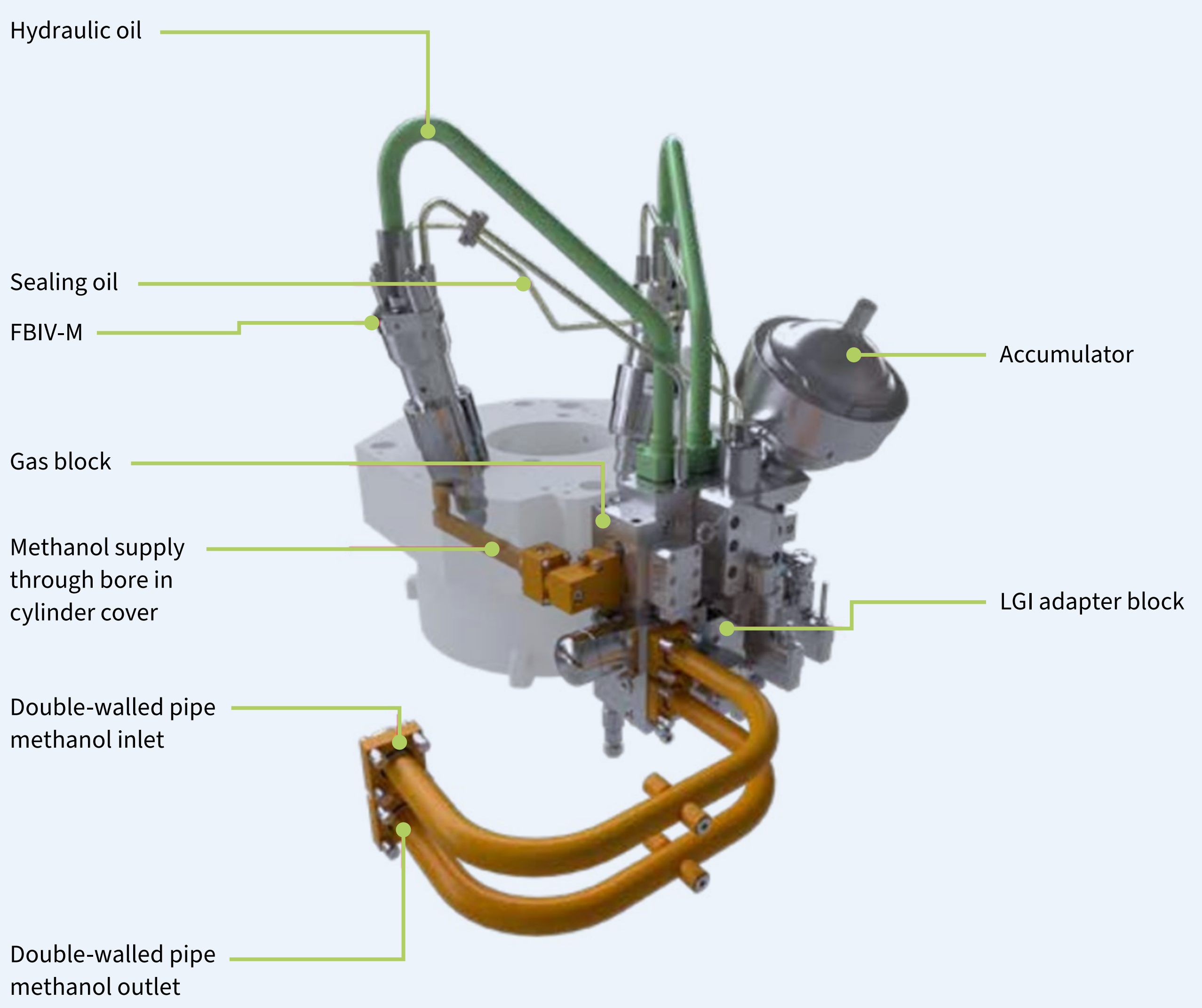
With high market demand, a parent test engine could be developed specifically for validating NOx requirements, and MAN is already starting this process for its 90-bore engines. Otherwise, two-stroke retrofit package availability will likely follow the delivery of similar newbuild engines.

Cylinder cover elements of the ME-LGIM concept are illustrated on the image below. Main features of the MAN methanol concept include:

- Fuel booster injection valves for injection of methanol (FBIV-M) into the combustion chamber around top dead centre
- Hydraulic control systems to control the fuel booster valve operation
- Sealing oil supply unit mounted on the engine to ensure that no methanol leakage occurs in the moving parts of the methanol injection system to the hydraulic control system
- Double-walled piping to distribute methanol to the individual cylinders
- Draining and purging system for removal of methanol from the engine
- Engine control system and safety system monitoring the methanol injection and combustion; engine reverts to diesel oil operation in case of alarms
- Off engine Fuel Valve Train (FVT) providing a block-and-bleed function between the fuel supply system and the engine
- Off engine automated methanol supply system with an embedded purge system

Ammonia

MAN started its first ammonia-fuelled, one-cylinder test engine in Copenhagen Q2 2023. A six-cylinder 60 bore test engine will begin operating at Mitsui Engineering & Shipbuilding's facility in Japan in January 2024 and the first ammonia-fuelled two-stroke engines are likely to enter service in 2026.



Methanol components and pipes on MAN ME-LGIM cylinder cover

The first engine size to be made available will be the 60 bore, which can be deployed in multiple vessel segments. There is also particular demand for 80 bore engines for large vessels on bulk trades, where national policies in Australia and Japan are accelerating interest in ammonia fuel. Following the same development logic as for methanol retrofits, MAN expects to be able to deliver the first ammonia retrofits for two-stroke engines from 2027.

While retrofit packages for other fuels can be developed in around six months, MAN noted that retrofit development may initially take up to a year for ammonia. This has both safety and commercial rationale: the challenges of handling ammonia mean that many novel ship systems will be used, as well as new engine features.

MAN noted that the further roll-out of ammonia-fuelled engines and retrofits is likely to be tightly controlled until early operational experience is gathered from the first vessels. A steady roll-out of the technology will help to identify teething issues, and to feed that experience back into engine and retrofit package designs.

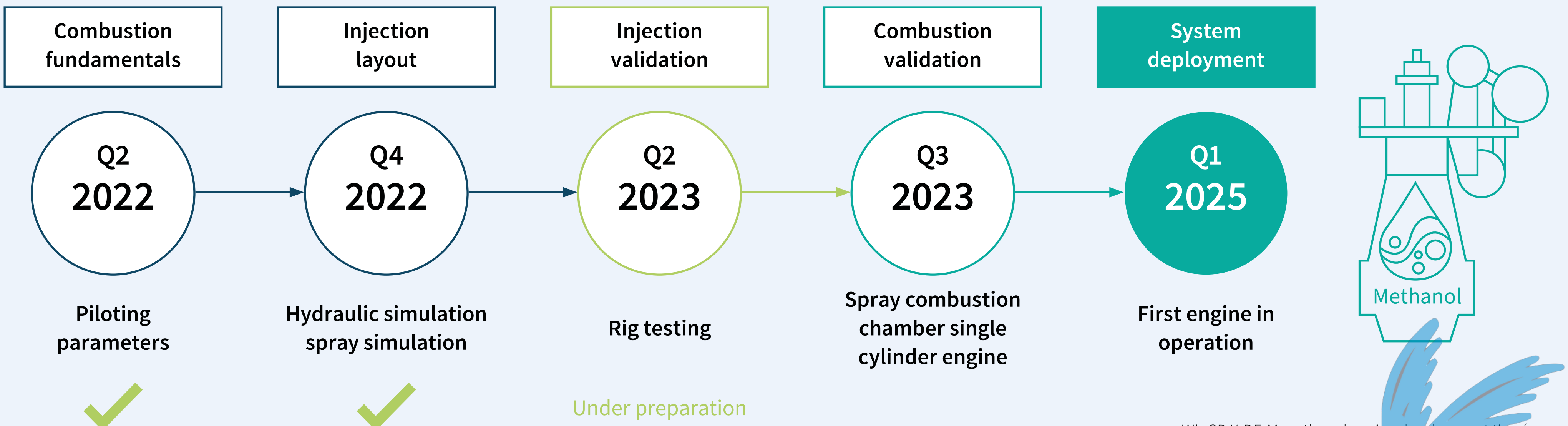
The fuel injection system design will be confirmed on test engines but is expected to be similar to the engine concept (LGI) used for MAN's liquid petroleum gas (LPG) fuelled engines. MAN is simultaneously working on adapting selective catalytic reduction NOx abatement technology to handle emissions, which will be further explored on the testbed. An off-engine ammonia catcher system is also under development to reprocess fuel system purges, effectively a closed fuel system that prevents venting of ammonia under normal operation. A retrofit package is likely to include new cylinder heads and engine piping, the fuel valve train, knock-out drums and a nitrogen separator (for onboard generation of nitrogen for purging and inerting).

WinGD

Methanol

WinGD's first methanol-fuelled newbuild engines, named X-DF-M, are expected to enter service in 2025. The company has determined that these engines will follow the Diesel-cycle combustion principle, with high-pressure injection, as opposed to the Otto-cycle low-pressure injection used for burning LNG in its existing dual-fuel X-DF engines. However, retrofit packages will be made available for all existing WinGD electronically controlled engines, covering both dual-fuel LNG and single-fuelled diesel engines.

While the first methanol engines are under development in partnership with engine builders in China and Korea, WinGD has already advanced a potential fuel injection concept, known as the Fuel Flexible Injector.



WinGD X-DF-M methanol engine development timeframe

This was developed as part of the pan-European HERCULES 2 marine engine innovation project and is designed with adaptable injection pressure for a range of liquid fuels, including conventional fuel oils as well as alcohol fuels including methanol and ethanol. The injector has already been used to investigate injection, combustion and emission properties of alcohol fuels. While it will require some further investigation before a final commercial concept is settled, this concept provides the basis for development.

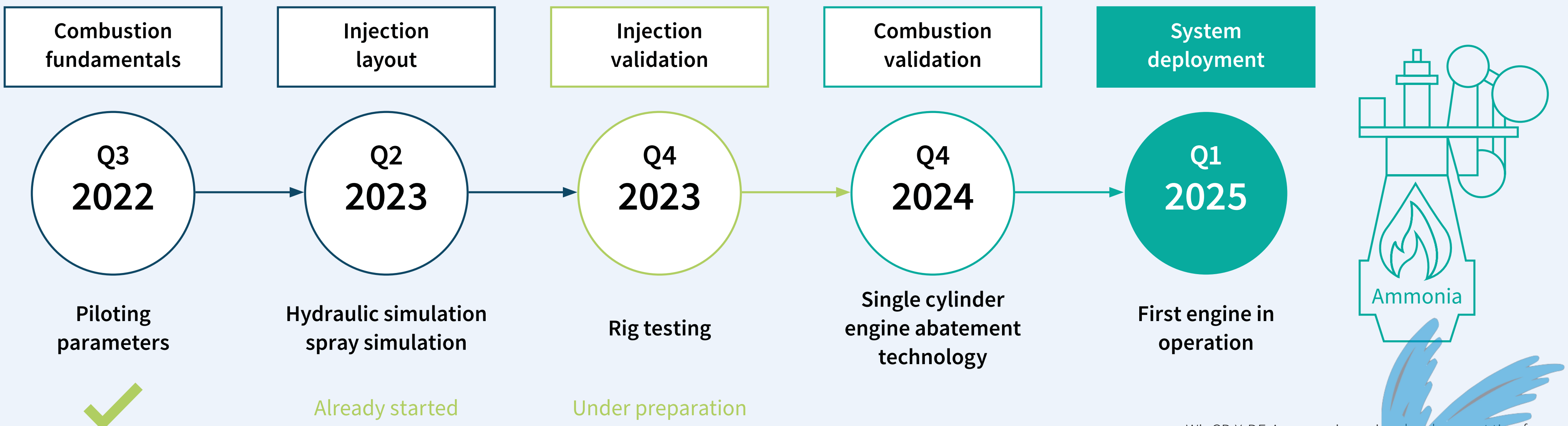
Development projects with engine builders indicate the initial bore sizes for which methanol capability will be available. In Korea, WinGD is working with HSD Engine on the 92cm bore engine, the X92-DF-M. The engine is most often deployed on large and ultra-large containerships, and the diesel-fuelled X92-B engine will be used as a base for adding methanol fuel technology. As part of the development project with HSD, WinGD will oversee combustion and injection concepts, exhaust aftertreatment requirements (for NOx and, if needed, N2O) and engine detail design. HSD will provide engine testing capabilities and deliver fuel supply and exhaust aftertreatment systems, as well as giving feed-back on engine manufacturing and assembly costs expertise.

WinGD's first announced order for a methanol-fuelled newbuild engine is also for the 92cm bore size. The company will supply ten-cylinder 10X92DF-M methanol-fuelled engines to four 16,000 TEU container vessels to be built for COSCO Shipping Lines at COSCO Shipping Heavy Industry's shipyard in Yangzhou, China, with delivery from 2025.

While conversion packages can take six months or more to follow the introduction of a new two-stroke engine, the unique circumstances of WinGD's first delivery to COSCO Shipping Lines will mean that retrofit development will be expedited. The fourth vessel in the series will be the first to have a newbuild X92DF-M engine installed from the beginning, while the earlier vessels will initially have methanol-ready X92-B engines installed and will be converted for methanol before entering service. WinGD anticipates that a newbuild 82cm-bore engine will be the next to enter service, with a retrofit package available shortly after. Other engine sizes will be developed based on market demand.

Ammonia

WinGD has announced concrete steps in its plans to develop ammonia-fuelled engines, which will be known as X-DF-A. In late 2021 it announced a timeframe for both methanol- and ammonia-fuelled engines, anticipating it would finalise an ammonia engine concept by 2025. In mid-2022 it signed a joint development project with Hyundai Heavy Industries to advance X-DF-A readiness for commercialisation. And in early 2023 it revealed another partnership, with alternative fuel specialist CMB.TECH, to jointly develop the first 82cm-bore ammonia-fuelled engines.



WinGD X-DF-A ammonia engine development timeframe

The X82DF-A partnership is the first ammonia two-stroke project with a publicly announced commercial end result; the aim is to develop engines for a series of ten 210,000 DWT bulk carriers that will be delivered in 2025 and 2026. WinGD has confirmed that a retrofit package for this engine size will be available six months to a year after the newbuild engine is completed, with further engine sizes already under development.

As with WinGD's methanol-fuelled engine, the ammonia-capable plant will be designed with high-pressure fuel injection, using a Diesel cycle combustion concept. Conversions will be possible from all current WinGD engines.

Wärtsilä

Methanol and ammonia

Wärtsilä's Fit4Fuels two-stroke fuel conversion is distinct from other two-stroke engine retrofit solutions in two ways. First, it is the only dedicated retrofit solution from a third-party supplier; Wärtsilä no longer designs two-stroke engines but is the global service provider for all WinGD designed engines, which includes both the Sulzer and Wärtsilä two-stroke engine brands. It is all these engines (again, if electronically controlled) for which the retrofit solution is applicable.

The second difference is that Wärtsilä proposes multi-fuel optionality within the same engine retrofit concept, albeit in stages. With relatively minor adjustments the solution can take vessels down two fuel pathways: from conventional fuel to LNG and then to ammonia; or from conventional fuel to methanol or ammonia. While an LNG to methanol pathway is technically feasible, the business case for such a route is slim, as the complexity of cryogenic storage and fuel handling equipment for LNG would require a relatively long payback time, while cryogenic capability is not required for methanol.

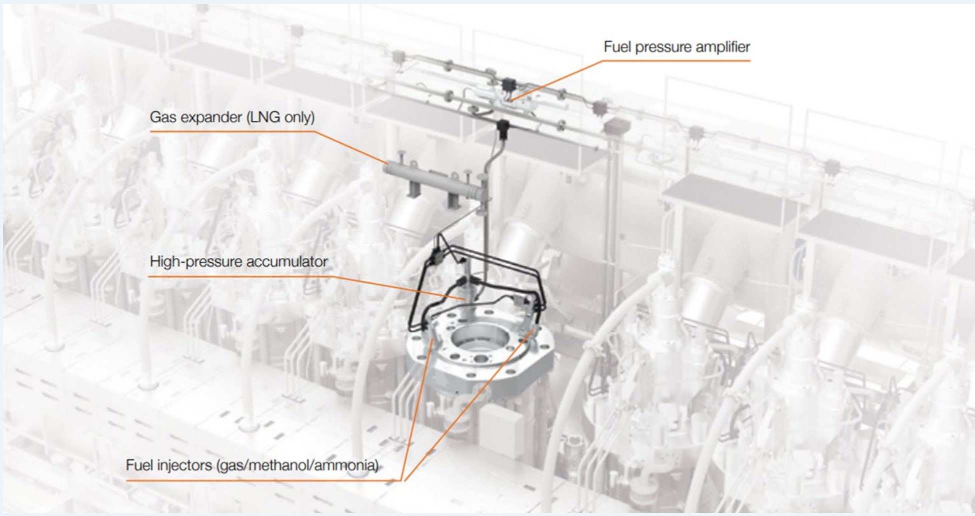
Moving from LNG to ammonia, much of the auxiliary technology can be retained. The concept is in the design stage but Wärtsilä's intention is to eliminate changes required when switching from LNG to ammonia, although issues such as component sizing will need consideration due to the greater volumes of ammonia that will be needed.

The Wärtsilä Fit4Fuels uses high-pressure injection but, unlike other two-stroke concepts for methanol and ammonia, allows for low-pressure fuel supply. This is achieved by adding an on-engine amplifier to reach the pressures needed for injection. To meet safety requirements, the booster and low-pressure and high-pressure pipes are contained in an enclosure which is continuously ventilated and monitored for leakages. Some adaptation may be required depending on the final form of ammonia safety requirements.

The use of on-engine fuel pressure boosting allows operators to save on the cost and space requirements of high-pressure fuel supply. To further reduce running costs, the on-engine fuel preparation processes are powered by excess energy from the engine's servo oil and jacket cooling water systems.

If high-pressure injection is needed the system can be adapted – for example running on high engine loads with minimum pilot fuel on LNG - but will not be needed for most retrofit cases. Overall, the Wärtsilä system aims to deliver a simpler and quicker installation as well as lower operating costs, while maintaining the fuel efficiency associated with high-pressure injection engines.

Wärtsilä will install its pilot concept on a large container ship vessel in early to mid-2024. The existing engine will be converted from conventional fuel to dual-fuel LNG, with the same engine being converted to ammonia around a year after the first retrofit. A full-scale demonstration of the concept as it will be installed on the pilot vessel has already taken place with the owner at Wärtsilä's test engine facility. In between the two conversions on the first pilot vessel, a second vessel is scheduled to become the first test installation for the platform's methanol capability.



Wärtsilä Two-Stroke Future Fuel Conversion Platform

Wärtsilä suggests that the concept results in a simpler installation than OEM-designed retrofit packages because it does not require adjustment of some components (including cylinder liners and gas admission valves) that would be needed to convert an engine from one standard engine type to another. The company is also working to ensure that the rest of the fuel storage and supply system is in place with multi-fuel capability, focusing initially on systems for the pilot installation that can handle both LNG and ammonia.

Four-stroke engines

MAN Energy Solutions

Methanol

While two-stroke methanol engines will be available as newbuild first, with retrofit packages developed later, for four-stroke engines the process has largely been reversed. Both MAN and Wärtsilä have started their methanol four-stroke developments with conversion solutions. In the case of MAN Energy Solutions, a retrofit is being developed that will deliver a methanol-capable 51/60 (51cm engine bore, 60cm stroke length) engine.

The first MAN 51/60 engines capable of using methanol will be retrofitted on a Stena ro-ro vessel and a Norwegian Cruise Lines cruise ship in late 2024 or early 2025. The retrofit solution is expected to be in series production from 2026. The solution can be applied to existing diesel-fuelled 48/60 and 51/60 engines. Covering multiple bore sizes with the same retrofit solution means that technology can reach market faster, while also ensuring that older engines are upgraded to the latest, most efficient bore size.

MAN is planning a two-stage development for its four-stroke methanol technology. Initially the retrofit solution will feature a port fuel injection concept, where an injector located in the air inlet will deliver methanol into the air intake stream prior to entering the combustion chamber. This low-pressure combustion concept is easier to apply to existing engines and requires less costly auxiliary equipment including lower pressure fuel supply. As well as allowing the solution to come to market quickly, this solution is also optimal for operations where diesel will be the main fuel, as methanol's availability as a marine fuel increases.

As methanol availability and use matures, MAN plans to introduce a high-pressure direct injection concept. This will be similar to injection on its Diesel-cycle two-stroke engines, with a fuel mix of diesel and methanol injected from separate needles directly into the combustion chamber at the top of the cycle. This concept will also be used for engines capable of using ammonia and hydrogen, with the different fuel requirements meaning that development of high-pressure injection will take longer than low-pressure port fuel injection.

MAN sees demand for methanol-fuelled four-stroke engine retrofits coming primarily from vessel applications where the engine is involved in propulsion – either directly or as part of a hybrid-electric power chain - including cruise, ferry and ro-ro segments. For the smaller engine bore sizes used for auxiliary power on larger vessels, there is less of a business case due to the lower fuel usage and smaller engine size.

The small engine size used as auxiliaries on deep-sea vessels means that retrofitting an engine for methanol would be as expensive as installing a new engine, while for bigger engines a retrofit is expected to be around 80% of the cost of a new engine. For auxiliary engines then, either installing new methanol engines or running existing engines on biofuels to lower emissions are more feasible options.

Ammonia

As described above, MAN is developing a high-pressure fuel injection concept that will be capable of handling ammonia fuel. Under the AmmoniaMot research project, which runs until the end of 2023 – MAN is developing a four-stroke, dual-fuel engine that can operate on ammonia. The project partners include the University of Munich (TUM), Neptun Ship Design, WTZ and Woodward L'Orange. A prototype of the fuel system has been installed on the test engine at WTZ Rosslau research institute, where the combustion concept for the new engine is being developed.

To date MAN has not put a timeframe on the development of newbuild four-stroke ammonia-fuelled engines or retrofit package availability.

Wärtsilä

Methanol

Wärtsilä delivered its first methanol engine conversion in 2015, retrofitting the ro-pax cruise ferry Stena Germanica's four Sulzer 8ZAL40S engines, an LR Classed ship. The engine conversions were undertaken one at a time while the vessel was in service, with the fuel supply system and tanks adapted at drydock – a project option that the company says is viable for future retrofits and could save considerable off-hire time.

The company developed a retrofit package for Z40 engines based on that project, although it has yet to be deployed and, as the engine is surpassed by more modern and efficient variants, is likely to remain a niche option. But that early retrofitting and fuel experience has fed directly into the design of Wärtsilä's newest engines. The Wärtsilä 32M is its first newbuild methanol engine, released in early 2022, and a retrofit package is available for diesel-fuelled Wärtsilä 32 engines.

The cruise sector is a key target for four-stroke methanol-fuelled engines, and Wärtsilä's latest release in the widely used 46-cm bore engine size – the Wärtsilä 46TS-DF - has been designed to facilitate future conversion to both methanol and ammonia fuel. Modular design enables fuel injection, piping and control systems to be replaced with more ease than in previous models. However, it is an earlier version of the 46cm-bore engine, the Wärtsilä 46F, that will become the first modern engine in Wärtsilä's four-stroke portfolio to be converted for methanol fuel. In April, the company announced that it will deliver engines for the fifth vessel in Celebrity Cruises' Edge series in late 2023. Two eight-cylinder Wärtsilä 46F engines will be converted for methanol at Chantiers de l'Atlantique shipyard before the newbuild vessel is delivered.

With methanol capability for newbuild engines and retrofit packages already available for the 32cm- and 46cm-bore sizes, Wärtsilä will shortly release details of its plans to roll-out methanol fuel technology across its four-stroke engine portfolio.

Wärtsilä has also developed a methanol fuel supply system, MethanolPac. The package includes the high-pressure methanol fuel pump unit, low-pressure pump module, fuel valve train, bunkering stations and tank instrumentation. MethanolPac will be installed on a wind turbine installation vessel under construction for Dutch ship operator Van Oord, which will be powered by the first Wärtsilä 32M in service.

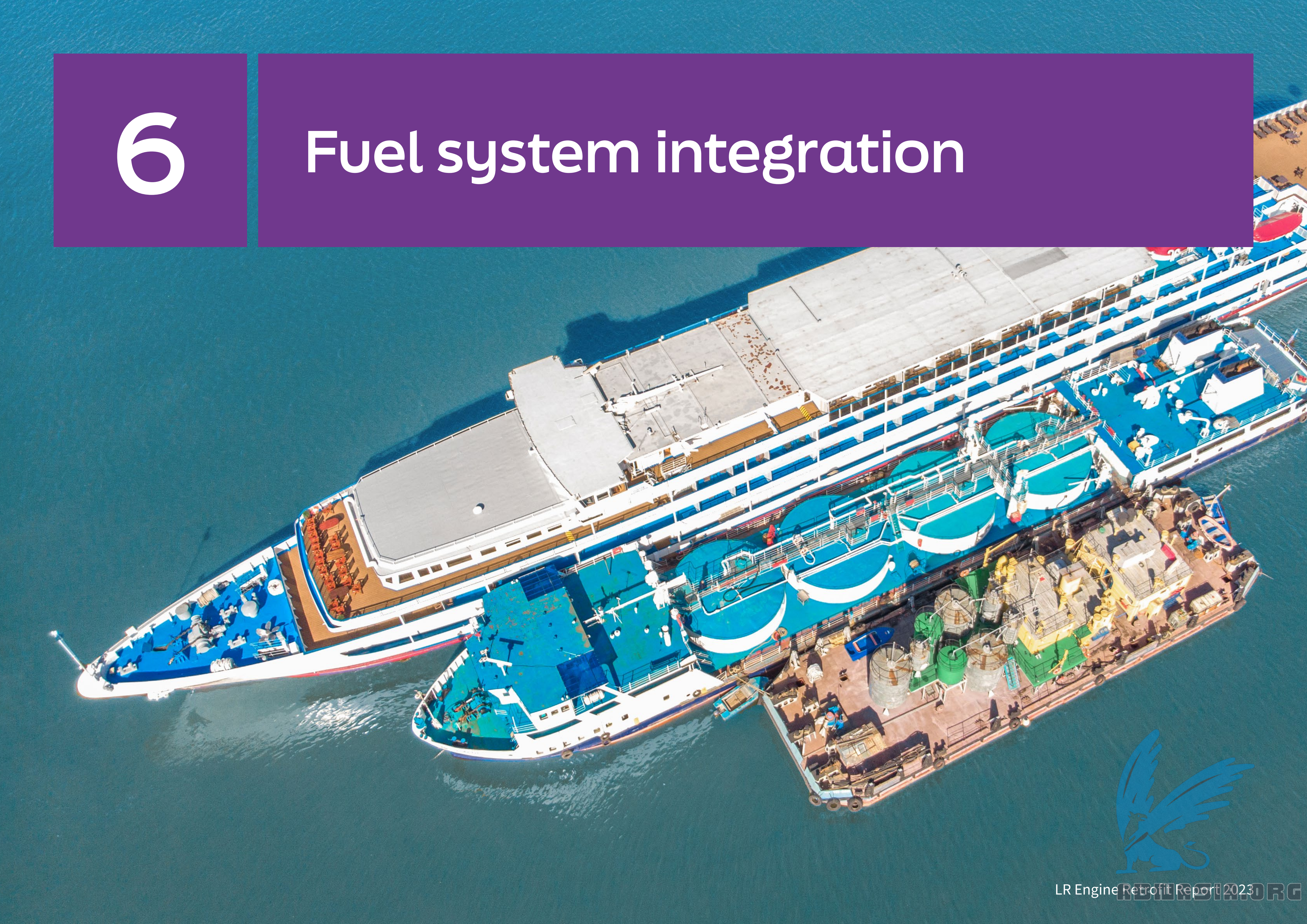
Ammonia

Wärtsilä currently has two ammonia-fuelled four-stroke test engines: one at its headquarters in Vaasa, Finland and the other undergoing trials with customers Knutsen OAS, Repsol Norway and Equinor at the Sustainable Energy Catapult Centre in Stord, Norway. The company reports that it has already proven an engine concept running on high-proportion ammonia blends of up to 70% ammonia so far and is currently confirming operations on pure ammonia (plus pilot fuel).

In 2022, Wärtsilä launched one of its highest-speed engines, the Wärtsilä 25, which it expects to be its first engine to be capable of running on ammonia fuel. Built in modular fashion to simplify conversion, like the 46TS-DF, the 25cm-bore engine also features injection timing and control concepts that the company says will be adaptable for ammonia fuel.

Wärtsilä anticipates that the technology concept for ammonia-fuelled four-stroke engines will be finalised this year and that engines will be commercially available soon afterwards. Beyond the Wärtsilä 25, it has yet to announce any concrete roll-out plans featuring other engine sizes, either for newbuilds or retrofit packages.

6 Fuel system integration



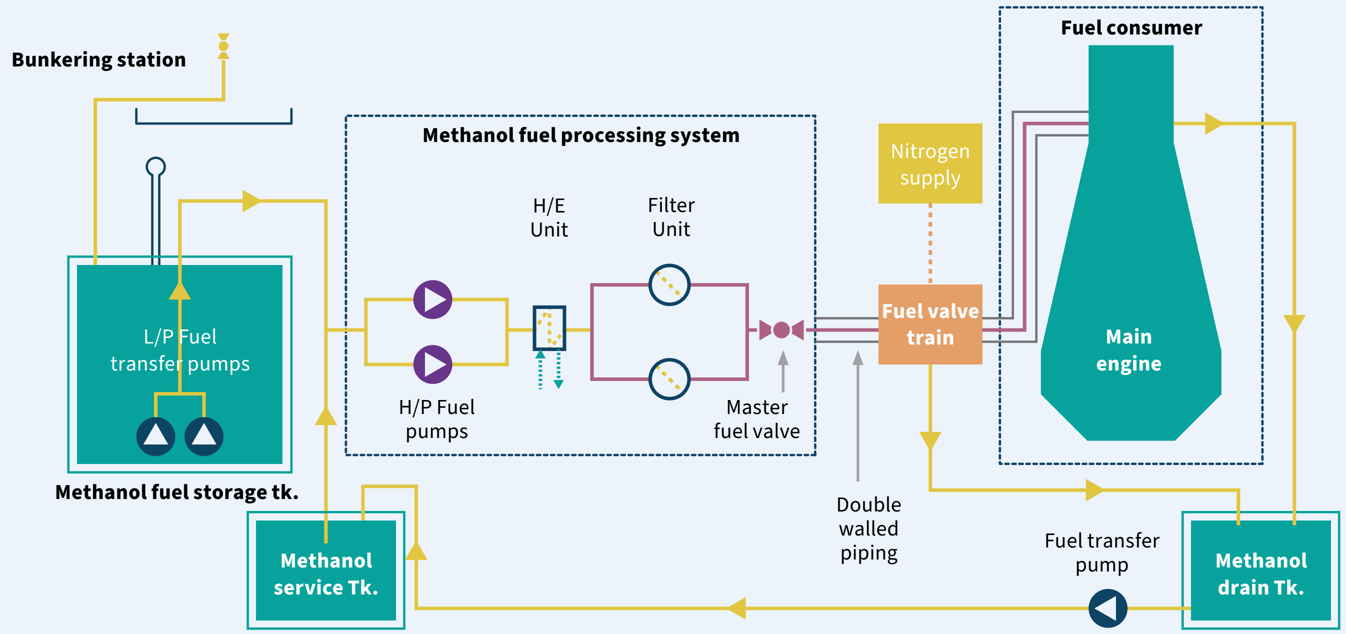
Integrating an alternative fuel system on existing vessels – including engine, fuel preparation and storage tanks as well as the associated control and safety features - holds particular challenges for retrofit projects.

Preparing vessels to use alternative fuels goes beyond installing fuel-capable engines. Fuel storage needs to be adapted both to meet the volume requirements of the new fuel as well as the safety demands of regulations and class rules. New fuel supply systems need to be introduced and contained in a safe area separate from the engine room. Fuel piping has to be modified, affecting bulkhead penetrations across the vessel. And new safety measures including venting, ventilation and fire prevention and control need to be applied.

Finding space for this new equipment in line with the stipulations of the IGF Code and class rules is particularly challenging for vessels originally designed for use with other fuels. In some ship designs, finding additional tank space, particularly while limiting the loss of cargo carrying capacity, is a particular design challenge. For example, one reason why container vessels are among the first merchant segments to consider alternative fuels is that the void spaces between the hull structure and existing fuel tanks allows for greater flexibility in adding tank space.

Fuel system

Methanol Storage, processing & supply system



Source: MAN ES, Lloyd's Register

Fuel storage

Methanol

Methanol is liquid at ambient temperatures and can be stored in tanks made from stainless steel, or mild steel coated with zinc silicate. This means that fuel tanks on existing vessels can be used if thoroughly cleaned and coated, provided they meet IGF Code requirements on tank location. Protective cofferdams are required around the methanol tank, except for areas below the lowest possible water line.

The tank must be inerted with a nitrogen blanket to reduce risk of flammability and corrosivity, which demands extra systems and safety considerations. If a nitrogen generator or storage facilities are installed outside of the engine room, the compartment must be fitted with a low oxygen alarm and independent mechanical ventilation.

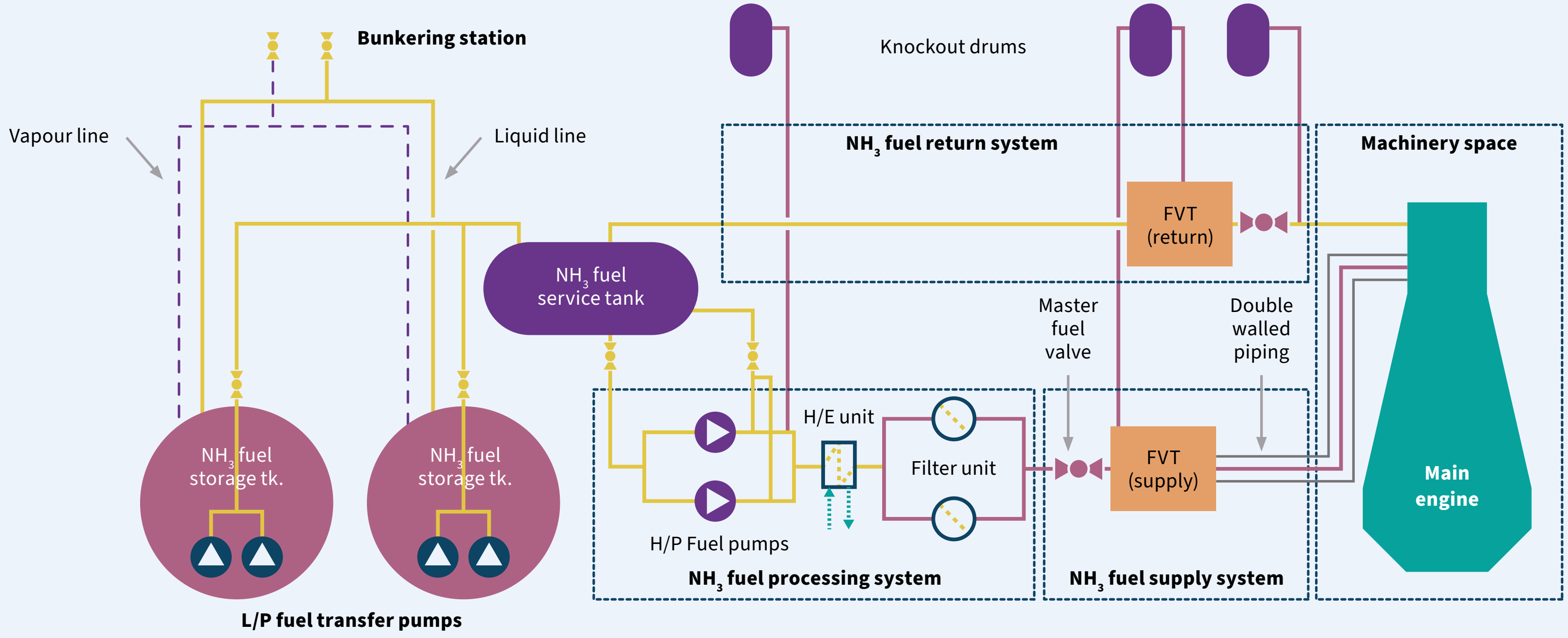
Ammonia

Ammonia can be stored as a liquid either by refrigeration below -33°C or under pressure in insulated structural tanks. Depending on the type of tank chosen, the secondary barrier, where required, must include additional features such as a pressure release system or drip trays with a leak detection and purging system. For integrated, membrane tanks, the ship supporting structure may act as a secondary barrier and insulating foam must be dense enough to accommodate high sloshing loads.

A reliquefication system or other means of tank pressure and boil off gas management is needed for non-pressurised ammonia tanks. "While rules for using ammonia cargo as fuel have yet to be developed, under the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), two independent boil-off management means are needed, requiring a reliquefaction system with at least one ammonia consumer (boiler or auxiliary engines) or two separate reliquefaction systems. However the IGC Code would first need to be amended, as use of ammonia cargo as fuel is currently prohibited."

Ammonia

Onboard arrangements



Key considerations for conversions:

- Finding an appropriate location for new fuel tanks that meets regulatory requirements on distance from side shell plating - and allows space for cofferdams, insulation, venting and reliquefaction systems – is the main challenge for alternative fuel retrofits.
- Assessing the impact of fuel storage requirements on vessel endurance and minimising loss of cargo capacity requires extensive ship design work.
- The size and location of fuel tanks has an impact on the vessel stability and may impose limitations to loading conditions. Stability checks must be made with various tank and loading conditions to ensure stability is maintained. To ensure longitudinal strength, the hogging moment in alternative loading conditions should be studied.
- Converting existing fuel tanks for methanol will need cleaning and surface preparation before coating, with particular attention to any internal supporting structures.

Fuel preparation room

Fuel pumps, fuel valve trains, heat exchangers and filters are contained in a fuel preparation room separate from the engine room. Fuel preparation room designs need to incorporate measures to minimise risk of exposure to leaks, including escape routes, internal separations, ventilation and leak containment measures including water curtain or spray systems.

Multiple methanol fuel supply systems are already commercially available while ammonia fuel supply systems are under development, and some have reached Approval in Principle.

Key considerations for conversions:

- Fuel preparation room needs to be sized based on selection of fuel supply system components.
- An airlock is required between fuel consumers and fuel preparation. Availability of suitable location close to the engine room to minimise pipe routing that could disrupt ship structural elements may be difficult to find on some existing vessels.
- Fuel preparation equipment needs to be purged and vented during fuel switching. These requirements and associated piping can also challenge existing ship configurations.

Fuel piping

For both methanol and ammonia, fuel pipes beyond the fuel preparation room in enclosed spaces must be double walled.

Key considerations for conversions:

- Complexity of pipe routing through existing ship structure and machinery space.
- Diameter of piping and additional space for pipe layout if using existing piping or piping routes, to account for larger volume requirements of methanol and ammonia.

Ventilation, venting and purging

Ventilation from tank spaces and fuel preparation rooms should be designed to avoid exposure to crew outside those areas.

For ammonia, accommodation ventilation also needs to be designed to minimise gas ingress. Gas detectors are needed at air inlets with an automated ventilation system to enable maximum recirculation if gas is detected.

Vent masts should be appropriately zoned and located away from accommodation and air intakes.

Fire detection, prevention and control

Vessels should be split into zones where gases are handled according to the IGF code, with explosion-proof equipment used in the appropriate zones. Gas detectors are required in many locations including fuel preparation rooms, double-walled pipes, air locks and cofferdams.

Spaces containing fuel preparation equipment are classified as Category A machinery spaces under SOLAS Reg II-2/9 with specific insulation and fire extinguishing requirements. Bunker stations, fuel preparation rooms and pump rooms near fuel tanks should be sprayable with water for ammonia or foam for methanol. Fixed firefighting systems should also be installed in the fuel preparation room. For methanol, a foam extinguishing system is required for the tank top and underfloor bilge area.

Further measures are needed for ammonia, potentially including water curtains or spray systems. These may be needed in and around the fuel preparation room, bunker station, tank connection spaces and accommodation block.

7 Retrofit capacity and capability

The complexity of vessel conversions means that only limited numbers of repair yards may initially be able to carry out such projects. Scaling up expertise will be crucial to meeting demand.

Fuel retrofits are more complex than most projects undertaken by repair yards. Converting the engine itself is a relatively straightforward process of installing prefabricated engine components.

Introducing these elements to an existing ship, designed with an entirely different fuel use in mind, requires skills that cannot always be taken for granted at repair yards, where the focus has traditionally been on restoring vessels based on an original design.

Required capabilities

The need for specialist skills in fuel retrofits places an inherent restraint on the industry's ability to meet the emerging demand for applying alternative fuels to existing vessels. Ship designers interviewed by Lloyd's Register highlighted three essential areas:

Naval architecture: The design and location of system elements including tanks, fuel preparation rooms and piping needs careful consideration to comply with safety requirements, particularly the need for venting and hazardous zones. Assessing the impact of each part on the vessel's structural strength and stability is also critical.

Electrical engineering: Enhanced monitoring (leak and fire detection), automated mitigation systems (including purging, firefighting, venting and ventilation), as well as more complex regulation of the fuel chain place new demands on vessel electrical and automation infrastructure. This will require greater electrical engineering skills from yards in order to adapt or where necessary install entirely new systems.

Fuel handling: Especially during the commissioning and testing stages of the retrofit project, yards will need to have the capacity to handle alternative fuels. Given the limited number of existing alternative fuelled vessels in operation and their relative recent introduction – limiting repair yards' exposure to these vessels – this places a constraint on the number of repair yards currently capable of handling these projects.

These requirements mean that several OEMs and designers expect only a very limited pool of repair yards initially capable of fuel conversions. One key indicator of capability is the type of work the repair yard has previously conducted. Those with experience in complex offshore projects, for example, would likely have the design and electrical engineering skills needed. Those that have undertaken conversions of vessels to floating production and storage facilities including FSRUs and FPSOs would have similar capabilities.

Another limiting factor is the availability of a skilled workforce. While some designers suggested that yards that lacked expertise in certain areas – welding stainless steel for example – could simply hire in new teams, this could be difficult. One designer noted:

"The green transition is happening everywhere, not just in maritime. Everybody wants our mechanical engineers."

Retrofit project timeframe

Ship designers and OEMs indicate that a retrofit project is likely to take around two months, depending on size of the vessel, the scope of changes required and the level of preparation (such as prefabrication of equipment) that can be achieved. This can be broken down into several stages:

- Removal of existing fuel system components – including installing new tanks or modifying existing tanks
- Modification of retained elements such as welding and drilling for pipe support
- Assembling and installing new components including engine package and fuel supply
- Electrical wiring
- Commissioning and testing
- Sea trial

However, ship owners planning a retrofit project will need to factor in much longer lead times to account for yard availability. A full retrofit project plan – from feasibility to adoption – is described in the chart below. Following an initial feasibility process, including initial design, a detailed design and engineering process could reasonably be expected to take up to five months before beginning the conversion at the yard.

The project timeframe below indicates the major milestones in terms of design approval that need to be achieved at each stage.

Retrofit Timeline

Feasibility (6-12 months)

Certifications and approvals

- RBC-1
- Preliminary appraisal of rules
- Approvals on principle (Optional)

Description

- Owner / Operator identifies conversion option based on technology, fuel, commercial and operational considerations.
- Initial Design and Safety Statement drafted by owner and appraised by class; report issued and areas for further investigation identified (RBC-1).
- Approvals in Principle for system / equipment / component designs can be issued, provisional on RBC process completion.

Design & Engineering (5 months)

Certifications and approvals

- RBC-2
- RBC-3
- RBC-4
- Approvals on principle (Optional)
- Detailed design approval
- Plan approval
- Equipment / component certification

Description

- Risk assessments, HAZID and further studies conducted to finalise initial designs (RBC-2 & RBC-3), perform HAZOP (RBC-4) and complete safety action recommendations.
- Consultation with flag state begins to address certification requirements.
- Approvals in Principle for system / equipment / component designs can be issued, after approval of RBC -2 deliverables.
- Detailed designs sent to class technical support office for plan approval before use of equipment and component fabricators.
- Equipment component certification begins - confirming the equipment to be installed is built in accordance with designs.
- Time allowed for delivery of pre-fabricated equipment /components to conversion site.

Conversion (2 months)

Certifications and approvals

- RBC-5
- Site survey

Description

- Conversion begins on completion of Construction, Installation, and Commissioning Assessment (RBC - 5a).
- Equipment / components being built on-site are surveyed and certified.
- Site survey: project manager assesses scope of retrofit (based on engineering designs, manufacturing certificates and installation plan) and certifies that installation has taken place according to design.
- Assessment for the Development of In-Service Documentation (RBC-5b) to be completed before adoption.

Adoption (1 week)

Certifications and approvals

- Flag approval
- Class approval

Description

- Class and flag certification completed following successful commissioning and sea trial.

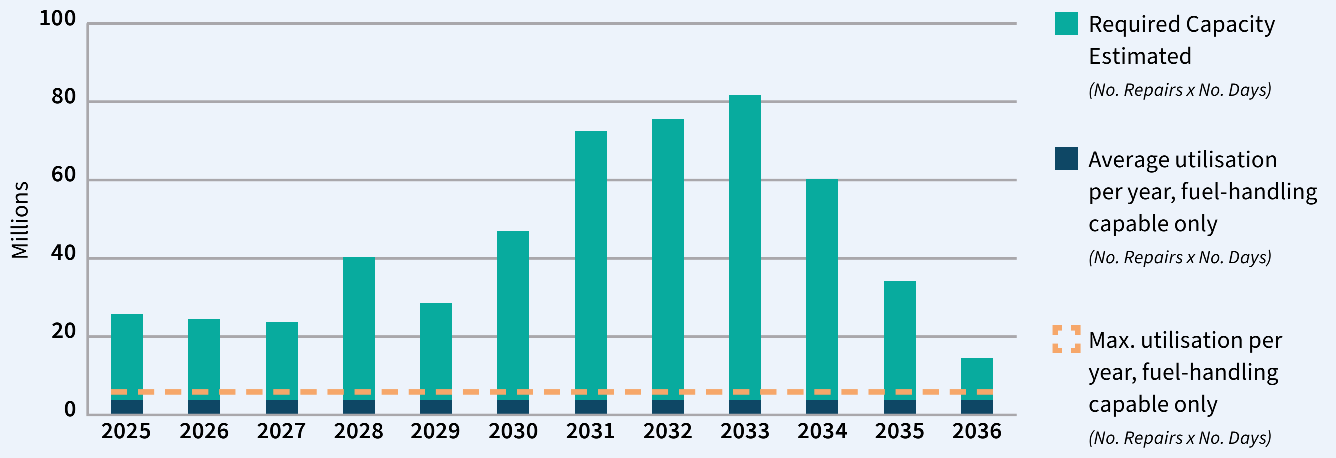
Scoping yard conversion capacity

Based on the above criteria, LR has identified a group of around 15 yards capable of handling alternative fuel retrofits. Allowing a 60-day conversion period, these yards could be capable of handling up to 308 conversions in total each year. Comparing this against the number of potential retrofit candidates for methanol and ammonia, it is clear that capacity would need to be increased dramatically to fulfil potential demand as interest in conversions increases.

Another factor for consideration in understanding capacity for retrofit projects is slot availability in repair yards. Repair capacity is already constrained and adding fuel retrofits will place further pressure on slots, potentially resulting in longer lead times and/or higher conversion costs.

It should be noted that this scoping of retrofit capability does not consider other constraints on the supply chain. For example, engine builders will need to balance the demand for newbuild engines with the growing demand for engine retrofit packages. If demand for newbuild engines is particularly high, this could lead to longer lead times for them to supply the required components for retrofits.

Required yard capacity for fuel conversions (No. Repairs x No. Days)



8 Training and Human Factors

For retrofitted vessels, ensuring that crew are trained, and human factor risks mitigated before a vessel is converted will be a key challenge for owners and operators.

At the early stage of alternative fuel use, the industry needs to ensure that the right frameworks are in place for crew skills and other factors affecting their health, safety and working conditions.

While design of alternatively fuelled vessels aims to minimise risk to crew, there are many other elements that ship operators will need to consider. Crew will need to be adequately trained in new systems, fuel handling and safety precautions. A wide range of factors will also need to be assessed to ensure that new working environments and practices do not adversely impact crew, for example by increasing risk of stress, fatigue or physical injury.

Unless processes are well established and crew already available prior to switching a vessel to new fuels, this will add cost and time to a conversion and will need to be factored into planning.

Human Factors

According to the UK Health & Safety Executive, "human factors refer to environmental, organisational and job factors, and human and individual characteristics, which influence behaviour at work in a way which can affect health and safety". Due to the novel properties that alternative fuels present and the changes to environment, organisation and job roles that their use will demand, it is critical that the various risks including those associated with human factors are understood so that appropriate operational and design safeguards, including engineering and administrative controls, can be put in place to reduce risk potentials to appropriate levels.

An inexhaustive list of areas that will need to be considered for human factor risks includes:

- **Ergonomics:** Ensuring the design of a vessel and its components address the intended users' capabilities and limitations given the operating circumstances and conditions.
- **Roles and responsibilities:** Demonstrating that responsibilities of crew are clearly defined and that personnel can safely perform activities with the resources provided.
- **Competency and training:** Crew have appropriate training for the relevant fuel, any new technologies and existing skills with heightened relevance, such as maintaining situation awareness and recognizing potential hazards.
- **Resourcing:** Enough crew are available to safely perform activities such as navigating, mooring, ship integrity and emergency response.
- **Procedures and processes:** How should control processes be developed to address the criticality of the risk, and how is delivery managed to promote adherence from the crew.
- **Occupational health:** Consideration of risks inherent with fuels and new systems, and how these can be mitigated via design, procedure and personal protection equipment.
- **Process safety hazards:** How to manage, and promote early recognition and response to, new circumstances where human activities may contribute to, exacerbate or prevent recovery from a hazard.

Assessing human factors - ammonia

Lloyd's Register Maritime Decarbonisation Hub (LRMDH) and the Maersk McKinney Moeller (MMM) Zero Carbon Shipping Centre commissioned Lloyd's Register's Human Factors advisory department to assist with the identification of human factors considerations related to the use of ammonia as fuel for reference designs of tanker, container and bulk carrier vessels. The work package included safety critical risk analysis, identifying key factors that contribute to performance and potential errors around bunkering, fuel preparation, maintenance and evacuation scenarios. A working environment health risk assessment examined vessel designs to identify the potential impact of noise, vibration, illumination, musculoskeletal stressors and exposure to chemicals or harmful substances. Finally, a competency needs analysis identified key areas of upskilling based upon a high-level concept of the new vessel operation.

The results point to the need to apply human factors engineering principles such as ergonomics within vessel design, as well ensuring enhancements to safety (and environmental) management systems and approach. Procedures must outline any new or modified planning, communication, competency / training and emergency response requirements. Other areas where modification would be needed include managing changes to operational and maintenance procedures, personnel-related matters including roles, responsibilities, staffing and interfaces with other organisations.

The table below highlights considerations in three areas that were assessed as having a high impact on crew health and safety.

Human Factors Considerations

Stages	Description	Impact on crew
Process and Procedures	Documented processes and work practices	• New ammonia specific policies, procedures or processes • Changes or modifications to operational and maintenance work practices, procedures and plans • Increase in requirements for risk assessment and employment of formal safe work practices • Changes to emergency response processes
Occupational Health Hazards	Exposure to toxicity, fire, noise, musculoskeletal risks, trips and falls etc.	• Toxicity • Materials / substance exposure • Manual handling • Ergonomics
Process Safety Hazards	Human involvement in the contribution, exacerbation and recovery of a major accident	• Changes to tank and system temperature and pressure management • New skills related to ammonia leak detection, isolation and repair • New explosivity and flammability conditions • Corrosivity potential • Updates to chemical management • New precautions with metals and materials

As an example of the impact of alternative fuels on workplace safety beyond the inherent properties of the fuels, the bunkering process could add ergonomic risk. In the case of ammonia bunkering, the project above assumed that bunker lines would be raised and fitted using lifting appliance / cranes but assisted locally by bunker team members. The ammonia lines connection was assumed to be quick-release system with relatively heavy, rigid hoses. The location and design of vessel bunker station would need to consider access of personnel and safe methods of working to assist with this process as opportunity for a range of occupational health hazards.

Maintenance tasks are one example of an area where new regimes or modified practices would be required. The incompatibility of ammonia with some metals and materials will need to be considered and reflected in the maintenance system and supply chain processes to ensure inappropriate substitutions are not allowed where ammonia could have negative impacts. Ammonia work may also require the use of new tools and techniques, which relevant personnel would need to be aware of and proficient in.

Alternative fuels training

The IMO Maritime Safety Committee has adopted amendments to the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) to include new mandatory minimum requirements for the training and qualifications of masters, officers, ratings and other personnel on ships subject to the IGF Code. However, training for fuels beyond LNG are at a very early stage of development.

As part of the Maritime Technologies Forum (MTF) initiative Lloyd's Register recently led a project aiming to identify gaps in industry training frameworks for safe use of alternative fuels: 'Operational Management to Accelerate Safe Maritime Decarbonization'[10].

The study examined three codes related to seafarer training – the IMO's STCW and International Management Code for the Safe Operation of Ships and for Pollution Prevention (ISM Code) and the ILO's Maritime Labour Convention (MLC) – and made recommendations on areas to accelerate readiness for using alternative fuels.

The core training scheme for seafarers, STCW, is currently undergoing an extensive review and onboard usage of alternative fuels is identified as one of the areas which is to be reviewed under this comprehensive review. This revision is likely to bring the Convention and Code up to date with developments regarding alternative fuels and latest technologies by 2028.

For ships falling under the IGF Code, amendments to the STCW by MSC.396(95) and MSC.397(95), adopted at the same time as the IGF Code, prescribe the required training under STCW. For those required to have advanced training this includes requirements on seagoing service and undertaking bunkering operations on IGF Code ships. This can be a challenge for the early adopters where availability of ships and training facilities may be an issue.

MTF has identified some gaps in relation to alternative fuels and STCW which can be summarised as regulatory uncertainty, insufficiencies within model courses, lack of training course development due to regulatory and market based uncertainties and inconsistent implementation of training.

The emerging theme is of a circularity in the factors affecting training availability. Training providers have to invest to develop courses, but have little incentive to do so while it is not clear that there is demand for a course. That clarity depends on industry uptake of the fuel, although ideally courses would be available before that point to ensure safe handling from the first operations.

Meanwhile industry uptake depends to a certain extent on training availability, as well as myriad other factors including clear regulations, fuel availability, bunkering infrastructure and technology readiness.

To advance the availability of training for alternative fuel use, and thus to potentially accelerate uptake, the project proposes that course providers are initially funded to develop alternative fuel syllabuses. This could be achieved through industry or regional mechanisms and would remove an element of risk from those investing in writing training courses.

The ISM Code is an international standard that is intended to ensure the safe operation of ships, to prevent human injury and loss of life at sea, and protection of the environment. It already has the framework for safe handling of hazardous fuels from the perspective of safety and pollution prevention provided that the equipment for handling, processing and storage of such fuels is certified as meeting all classification and statutory requirements when installed, the following Safety Management System (SMS) enhancements/mitigating measures should be implemented:

1. An additional risk assessment carried out by the company must identify and assess all reasonably foreseeable hazards posed by these fuels.
2. Crew must be certified as per national and international requirements.
3. Internal audits and periodic reviews should be carried out to confirm that the crew is adequately trained and familiar with the SMS procedures for handling alternative fuels and that the SMS has been implemented effectively.

MTF has identified some gaps in relation to alternative fuels and ISM Code's implementation which can be summarised as:

- Uncertainty related to Safety Management System requirements development and implementation.
- Uncertainty related to emergency procedure development.
- Uncertainty related to maintenance activities.
- Lack of familiarity of risks, hazards and control measures in terms of alternative fuels.

The full MTF report can be downloaded here:

https://www.maritimetechnologiesforum.com/documents/report-2023-04-20-MTF-operational-management.pdf

Summary of identified key gaps and recommendations for closing:

	Gap	Recommendation for closing
ISM-1	Uncertainty related to Safety Management System requirements development and implementation.	The development of a guidance document which can be produced by industry and submitted to the IMO.
ISM-2	Uncertainty related to emergency procedure development.	IMO may require industry stakeholders to develop a list of emergency scenarios, drills and associated guidance.
ISM-3	Uncertainty related to maintenance measures.	IMO may need to define, potentially based on industry proposals, and mandate the inclusion of measures to address maintenance of alternate fuel systems within the Safety Management System.
ISM-4	Lack of familiarity of risks, hazards and control measures.	All relevant industry stakeholders may need to identify training needs, develop training materials and provide training.
STCW-1	Regulatory uncertainty.	Industry guidelines for model courses may be developed to encourage and support swift regulatory change.
STCW-2	Insufficiencies with model courses.	Incentivise relevant industry stakeholders to collaborate with training providers.
STCW-3	Lack of incentives for training course developers.	Public and private funding may be provided to training course developers.
STCW-4	Inconsistent implementation of training.	Flag states could review the training materials and audit the training providers to ensure consistent delivery in line with IMO model courses.
MLC-1	Lack of reference to alternative fuels.	Reference to alternative fuels could be made in part B of the Code and international guidelines.

Note: Numbering above indicates perceived urgency to close the identified gaps.

9 Investment case and economic feasibility

Fuel availability, retrofit cost and carbon pricing will play key roles in determining the viability of engine conversions. In some segments they are already becoming a feasible prospect.

Assessing investment readiness
(to view summary table go to Appendix)

To assess the current business attractiveness of fuel conversions across selected deep-sea vessel segments – cruise, container, bulk carrier and tanker – LR analysed market structure and orderbook developments to derive the Investment Readiness Level (IRL). This grades investment readiness on a six-point scale as detailed below.

IRL	Level description
1	Hypothetical commercial proposition
2	Commercial trial, small scale
3	Commercial scale up
4	Multiple commercial applications
5	Market competition; Driving widespread development
6	Bankable asset class

Container vessels

The **container** segment is the first part of the merchant fleet beyond methanol tankers to welcome methanol-fuelled vessels, driven by orders from Maersk, COSCO and CMA CGM. A total of 76 vessels are on order as of May 2023. The first retrofit engine projects have also been confirmed by WinGD, although they will be destined for new vessels, with diesel engines installed and then converted to methanol engines before the vessels enter service.

Beyond these initial orders, there are a substantial number of owners seeking quotes from OEMs on up to 100 potential retrofit candidates, at time of publication. One large tonnage owner confirmed that methanol – both from newbuild and as retrofit – was likely to be among a menu of decarbonisation options offered to its charter customers. The same owner noted that ammonia retrofits, at this time, were unlikely to be on the same menu.

Container retrofit type	IRL
Methanol	2
Ammonia	1

While a retrofitted methanol-fuelled container ship has yet to enter service, the considerable volume of interest at a commercial stage indicates that the business case for methanol retrofits has gone beyond a hypothetical proposition, placing it at **IRL 2.**

The case for an ammonia retrofit market in the container sector has yet to emerge. Although there are 87 ammonia-ready vessels in service and on order – primarily LNG-fuelled vessels where cryogenic fuel handling makes conversion to ammonia technically feasible in principle – there are no vessels yet confirmed as entering service using ammonia, or with ammonia conversions planned. This places the ammonia retrofit proposition at **IRL 1.**

Cruise vessels

Interest in methanol retrofitting is emerging rapidly in the cruise sector; in one notable example, Norwegian Cruise Lines announced to investors that it has added US$1.2 billion to the contract cost of building four vessels due for delivery in 2027 and 2028 in order to add methanol capability. The first modern methanol-fuelled cruise vessels will feature engines modified for the fuel, evidencing the capability for future retrofits. This places methanol retrofits for cruise vessels at **IRL 2.**

Cruise retrofit type	IRL
Methanol	2
Ammonia	1

The case for ammonia retrofitting of cruise vessels is challenging due to the toxic nature of the fuel and the risk of public exposure both onboard and at city-centre ports. With no confirmed orders and very little market interest to date, the low investment attractiveness of ammonia conversions for cruise vessels is represented in a rating of **IRL 1.**

Bulk carriers

The **bulk carrier** market faces some structural challenges in uptake of alternative fuels that narrow the business case compared to other segments. As the majority of vessels are relatively simple ships, any additional capex must be considered carefully. Traditionally uptake of energy efficiency solutions has been very low as a result, and a cast-iron justification (such as a definitive regulatory driver or market-based measure) will be needed for extra expenditure.

Bulkers' exposure to the ad hoc, tramp shipping market, as well as the range of ports that the ships need to be able to reach in order to work in these markets, also means that flexibility is critical. Owners are therefore unlikely to be keen to invest in fuels which could have limited availability initially, due to the restrictions this might place on their operating area.

Bulk carrier retrofit type	IRL
Methanol	1
Ammonia	1

There are however early signs that bulk carrier operators are starting to move towards alternative fuels as decarbonisation signals become stronger. Three methanol-capable bulk carriers have been ordered and a handful of projects are being investigated at feasibility study stage. Orders for ammonia-fuelled bulk carriers are also emerging, likely due to the growing prospect of ammonia availability for some key long-term trades. However, as retrofitting interest has yet to emerge for either fuel, both ammonia and methanol conversions for bulk carriers remain at **IRL 1.**

Tankers

The **tanker** market is divided into several sub-segments, each of which have varying dynamics that influence the likely uptake of alternative fuels. Tankers designed to carry either methanol or ammonia are the most likely candidates to also be fuelled by their cargoes, and several methanol-fuelled methanol carriers are already in service. LPG tankers could also conceivably be powered by ammonia engines, while other cargoes could have synergies with methanol as a fuel.

Tanker retrofit type	IRL
Methanol	1
Ammonia	1

in methanol among operators of large vessel sizes such as Aframax and LR tankers, but little interest in ammonia. This may be due to the shorter lifespan of tankers compared to other segments, owing to the requirements of the large charterers that dominate the market. Alternative fuel uptake will likely be driven by the requirements of these charterers. To date limited uptake at newbuild stage translates to even less interest in retrofitting, meaning that both ammonia and methanol conversions for tankers have yet to establish a business case and remain at **IRL 1.**

Techno-economic scenarios

Fuel costs

To shed light on how the retrofitting for alternative fuels could affect the costs of owners and operators – and the impact of timing on post-retrofit costs - LR conducted a simple techno-economic analysis. The following basic operating profiles were considered:

	Sailing days per year	Daily fuel consumption (tonnes)
Ultra Large Container Ship	280	200
Newcastlemax Bulk Carrier	275	53
Very Large Crude Carrier	264	80
180,000 GT Cruise Vessel	264	280

The following scenarios were modelled. The high-cost scenario is similar to fuel prices as anticipated to the end of the decade, with a carbon tax somewhat higher than today's EU ETS value. The low-cost scenario features fuel costs and a carbon price that could realistically be expected to be achieved only close to 2050. In this way the scenarios represent a sliding scale of costs and can be used to indicate when a move to alternative fuels is feasible.

This simple techno-economic model makes omissions and assumptions which would need to be accounted for in any real-life techno-economic study. Both ammonia and methanol are treated as having zero exposure to carbon taxes, which will not necessarily be the case under FuelEU Maritime, for example. Pilot fuel needed for dual-fuel engines, which could be fossil-based and represent around 5% of fuel use, has also been excluded. So too has the potential cost of taxes on other greenhouse gas emissions, such as N2O. See end note for details of further assumptions[11].

	High-cost scenario	Low-cost scenario
VLSFO (USD/mt)	620	620
Methanol (USD/mt)	1222	757
Ammonia (USD/mt)	1200	655
Carbon Tax (USD/mt/CO_2)	100	350

The results of this modelling indicate that using renewable methanol or ammonia today – the high-cost scenario - would more than double the fuel costs for vessels in all segments, factoring in a global carbon tax level of US$100 per tonne. For vessels with greater fuel consumption – notably the large cruise and container ships - the additional fuel costs in a year approach the price of a conventional newbuild vessel.

This scenario, which most accurately reflects today's market, highlights the challenges facing operators considering a switch to alternative fuels, whether on existing or newbuild vessels. Carbon pricing, which at US$100 more than doubles the fuel bill of ship operators using conventional fuels, would need to reach much higher levels for alternative fuels to be viable.

The cost of renewable fuels would also need to drop (or the cost VLSFO increase) dramatically. The low-cost scenario, in which both ammonia and methanol decrease in price by close to 50% and the carbon price reaches an extremely high US$350, is just beyond the tipping point at which alternative fuels become cheaper than continued use of conventional fuels. The main dynamic for owners to consider before investing is when this tipping point will be reached.

One element for consideration is how the use of alternative fuels will affect the fuel supply business model across the industry. To reduce costs, operators will need to secure alternative fuel supply at very favourable prices. This is most likely achievable through long-term supply agreements or business partnerships. Several fuel supply agreements of this sort have already been announced for both methanol and ammonia, while initiatives such as Green Corridors could also help secure sustainable fuel supply between partner ship operators and fuel producers.

ULCS, high-cost scenario

	VLSFO	Methanol	Ammonia
Fuel consumption (mt)	56,000.00	117,065.33	125,247.31
Fuel cost (USD)	34,720,000.00	143,053,829.15	150,296,774.19
Emitted CO_2 (mt)	174,384.00		-
Carbon tax (USD)	17,438,400.00	-	-
Total cost (USD)	52,158,400.00	143,053,829.15	150,296,774.19
Premium v VLSFO (USD)		90,895,429.15	98,138,374.19

ULCS, low-cost scenario

	VLSFO	Methanol	Ammonia
Fuel consumption (mt)	56,000.00	117,065.33	125,247.31
Fuel cost (USD)	34,720,000.00	88,618,452.26	82,036,989.25
Emitted CO_2 (mt)	174,384.00	-	-
Carbon tax (USD)	61,034,400.00	-	-
Total cost (USD)	95,754,400.00	88,618,452.26	82,036,989.25
Premium v VLSFO (USD)		(7,135,947.74)	(13,717,410.75)

Newcastlemax, high-cost scenario

	VLSFO	Methanol	Ammonia
Fuel consumption (mt)	14,575.00	30,468.34	32,597.85
Fuel cost (USD)	9,036,500.00	37,232,313.57	39,117,419.35
Emitted CO_2 (mt)	45,386.55		
Carbon tax (USD)	4,538,655.00	-	
Total cost (USD)	13,575,155.00	37,232,313.57	39,117,419.35
Premium v VLSFO (USD)		23,657,158.57	25,542,264.35

Newcastlemax, low-cost scenario

	VLSFO	Methanol	Ammonia
Fuel consumption (mt)	14,575.00	30,468.34	32,597.85
Fuel cost (USD)	9,036,500.00	23,064,534.67	21,351,591.40
Emitted CO_2 (mt)	45,386.55		
Carbon tax (USD)	15,885,292.50		
Total cost (USD)	24,921,792.50	23,064,534.67	21,351,591.40
Premium v VLSFO (USD)		(1,857,257.83)	(3,570,201.10)

VLCC, high-cost scenario

	VLSFO	Methanol	Ammonia
Fuel consumption (mt)	21,120.00	44,150.35	47,236.13
Fuel cost (USD)	13,094,400.00	53,951,729.85	56,683,354.84
Emitted CO_2 (mt)	65,767.68		
Carbon tax (USD)	6,576,768.00		
Total cost (USD)	19,671,168.00	53,951,729.85	56,683,354.84
Premium v VLSFO (USD)		34,280,561.85	37,012,186.84

VLCC, low-cost scenario

	VLSFO	Methanol	Ammonia
Fuel consumption (mt)	21,120.00	44,150.35	47,236.13
Fuel cost (USD)	13,094,400.00	33,421,816.28	30,939,664.52
Emitted CO_2 (mt)	65,767.68		
Carbon tax (USD)	23,018,688.00		
Total cost (USD)	36,113,088.00	33,421,816.28	30,939,664.52
Premium v VLSFO (USD)		(2,691,271.72)	(2,482,151.77)

Cruise, high-cost scenario

	VLSFO	Methanol	Ammonia
Fuel consumption (mt)	73,920.00	154,526.23	165,326.45
Fuel cost (USD)	45,830,400.00	188,831,054.47	198,391,741.94
Emitted CO_2 (mt)	230,186.88		
Carbon tax (USD)	23,018,688.00		
Total cost (USD)	68,849,088.00	188,831,054.47	198,391,741.94
Premium v VLSFO (USD)		119,981,966.47	129,542,653.94

Cruise, low-cost scenario

	VLSFO	Methanol	Ammonia
Fuel consumption (mt)	73,920.00	154,526.23	165,326.45
Fuel cost (USD)	45,830,400.00	116,976,356.98	108,288,825.81
Emitted CO_2 (mt)	230,186.88		
Carbon tax (USD)	80,565,408.00		
Total cost (USD)	126,395,808.00	116,976,356.98	108,288,825.81
Premium v VLSFO (USD)		(9,419,451.02)	(18,106,982.19)

Retrofit cost and charter rates

Impact on fuel costs is just one element to be considered before retrofitting. In many cases, such as vessels operated under time charters, the fuel bill and the capital cost are borne by separate parties in shipping. For owners investing in a vessel conversion, understanding the charter premium their vessels can command will be another essential consideration. Conversely for charterers, understanding what rates owners will charge for their converted vessels will need to be factored alongside the cost of alternative fuels.

The minimum charter premium an owner will need to ask for is dependent on retrofit costs. Given the relative immaturity of both methanol and ammonia engine technology, let alone retrofits, these costs remain relatively uncertain. For newbuild methanol vessels, there is limited evidence pointing to the fact that engines will cost similar to dual-fuel LNG equivalents. However fuel storage and fuel handling equipment will cost less, as methanol does not require cryogenic storage. For ammonia, which requires as yet un-commercialised engine technology, fuel storage and handling, and additional safety technology, overall costs will be significantly higher.

According to the European Maritime Safety Authority publication Ammonia as a Marine Fuel[12], **"the total cost for retrofitting to an ammonia-fuelled ship, equipped with a 10-16 MW 2 stroke engine will be USD 10m-13m, depending on the type and size of the vessel, original engine and especially the number of retrofits being undertaken."**

The example below shows that an owner of a Newcastlemax vessel would need to charge an 11% premium on current charter rates (at time of publication) to amortise the cost of a US$10 million retrofit over ten years, even without factoring in inflation or any requirement for increaed profit margin on alternative fuelled vessels. This amounts to an extra US$1 million a year on the charter cost for the operator, on top of the cost of the new fuel. This would cut deeply into the roughly US$2-3.5 million saving an operator could make under the low-cost scenario for Newcastlemax vessels above.

Vessel TC Rate (USD/day)	26,500.00
Annual Working Days	344
Retrofit Cost (USD)	10,000,000.00
TC Duration (years)	10
TC Premium (USD/day)	2,906.98
TC Premium (%)	11%

References

[1] ISWG-GHG 13/3

[2] MEPC 79/INF.29

[3] See NASA definition, https://www.nasa.gov/directorates/heo/scan/engineering/technology/technology_readiness_level

[4] https://www.lr.org/en/marine-shipping/maritime-decarbonisation-hub/zcfm/

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

[6] MSC.1/Circ.1212, Guidelines on Alternative Design and Arrangements for SOLAS Chapters II-1 and III (2006)

[7] MSC.1/Circ.1621, Interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel

[8] Lloyd's Register Rules and Regulations for the Classification of Ships using Gases or other Low-flashpoint Fuels, July 2022

[9] https://www.hse.gov.uk/humanfactors/introduction.htm

[10] Operational Management to Accelerate Safe Maritime Decarbonization, Maritime Technologies Forum, April 2023

[11] Notes on fuel cost model assumptions:

Alternative fuel costs: The fuel cost for renewable methanol and ammonia were taken from the LR/UMAS Techno-economic assessment of zero carbon fuels, March 2020.

Carbon pricing: Under EU's ETS scheme the carbon price reached €100 per tonne of CO_2 emitted in early 2023 and is expected to continue to rise. This will be supplemented by further carbon pricing exposure including FuelEU Maritime penalties and any other market-based measures that may emerge from IMO or other countries and regions. The carbon tax value should be taken to represent the carbon cost faced by operators globally, although in reality they are likely to face a range of regional and international regimes.

Alternative fuel volumes: The different volumetric energy densities of VLSFO, ammonia and methanol need to be considered when making comparisons, as lower energy density means greater bunker volumes are needed. More than twice as much fuel will need to be bunkered for methanol and ammonia as for VLSFO to bring the same amount of energy onboard. The following lower calorific values (LCV) were used:

VLSFO: 0.0416 MJ/g

Methanol: 0.0199 MJ/g

Ammonia: 0.0186 MJ/g

Greenhouse gas intensity: Under the FuelEU Maritime Directive and the EU ETS, renewable fuels are allocated an emissions intensity factor that indicates the amount of carbon for which emitters will be charged. For ammonia, which contains no carbon, this is zero. For methanol, the value is calculated based on a methodology that includes considering production process, feedstocks and supply chain emissions. These are close to zero for fully renewable e-methanol and are considered zero here. For VLSFO, a standard GHG intensity factor of 3.114 gCO_2/gFuel is used.

[12] European Maritime Safety Agency (2022), Update on potential of biofuels in shipping, EMSA, Lisbon: https://www.emsa.europa.eu/publications/download/7322/4833/23.html

A1 Appendix 1

Investment, Community and Technology readiness levels by fuel and sector IRL/CRL/TRL

Sector	Fuel type	IRL	CRL	TRL: 4 stroke engine	TRL: 2 stroke engine	TRL: Fuel handling & storage
Bulk Carrier	Ammonia	1	1	3	3	2
	Methanol	1	4	5	4	5
Container ship	Ammonia	1	1	3	3	2
	Methanol	2	4	5	4	5
Cruise	Ammonia	1	1	3	N/A	2
	Methanol	2	4	5	N/A	5
Tanker	Ammonia	1	1	3	3	2
	Methanol	1	4	5	4	5

TRL	Level description
1	Basic principle observed
2	Technology concept formulated
3	First assessment of feasibility concept and technologies
4	Validation of integrated prototype in test environment
5	Testing prototype in user environment
6	Pre-production product
7	Low scale pilot production demonstrated
8	Manufacturing fully tested, validated and qualified
9	Product fully operational

IRL	Level description
1	Hypothetical commercial proposition
2	Commercial trial, small scale
3	Commercial scale up
4	Multiple commercial applications
5	Market competition; Driving widespread development
6	Bankable asset class

CRL	Level description
1	Identifying problem
2	Initial testing of proposed solution(s) together with relevant stakeholders
3	Proposed solution(s) validated by relevant stakeholders in the area
4	Solution(s) demonstrated in relevant environment and in co-operation with relevant stakeholders
5	Proposed solution(s) as well as a plan for societal adaptation complete and qualified
6	Actual project solution(s) proven in relevant environment

A2

Appendix 2

What does 'zero emissions' mean?

The terms used in this report use the definitions found in document ISWG-GHG 13/3/9, which provided a basis for describing the greenhouse gas intensity of fuels during the revision of IMO's strategy for the reduction of greenhouse gas emissions from ships.

Absolute zero is used to describe an energy source that produces no direct or indirect GHG emissions across the full Well-to-Wake lifecycle. To be more specific, 'absolute zero' describes where there are no emissions of carbon dioxide (CO_2) or other greenhouse gases (GHG) across all scopes, i.e., where there are no direct emissions from fuel consumption or indirect emissions from energy purchased or any GHG emissions from production to end use.

As an example, while ammonia contains no carbon, there are GHG emissions associated with its production, which currently mainly using natural gas. Even ammonia produced through renewable electricity would likely have GHG emissions associated with its production and supply.

Net-zero emissions are achieved when anthropogenic emissions of greenhouse gases to the atmosphere are balanced by anthropogenic removals over a specified period. Where multiple greenhouse gas emissions are involved, the quantification of net-zero emissions depends on the climate metric chosen to compare emissions of different gases (such as global warming potential, global temperature change potential, and others, as well as the chosen time horizon).

As an example, methanol contains carbon and so will always have GHG emissions associated with its use, but these can be balanced out by the use of captured carbon in its production.

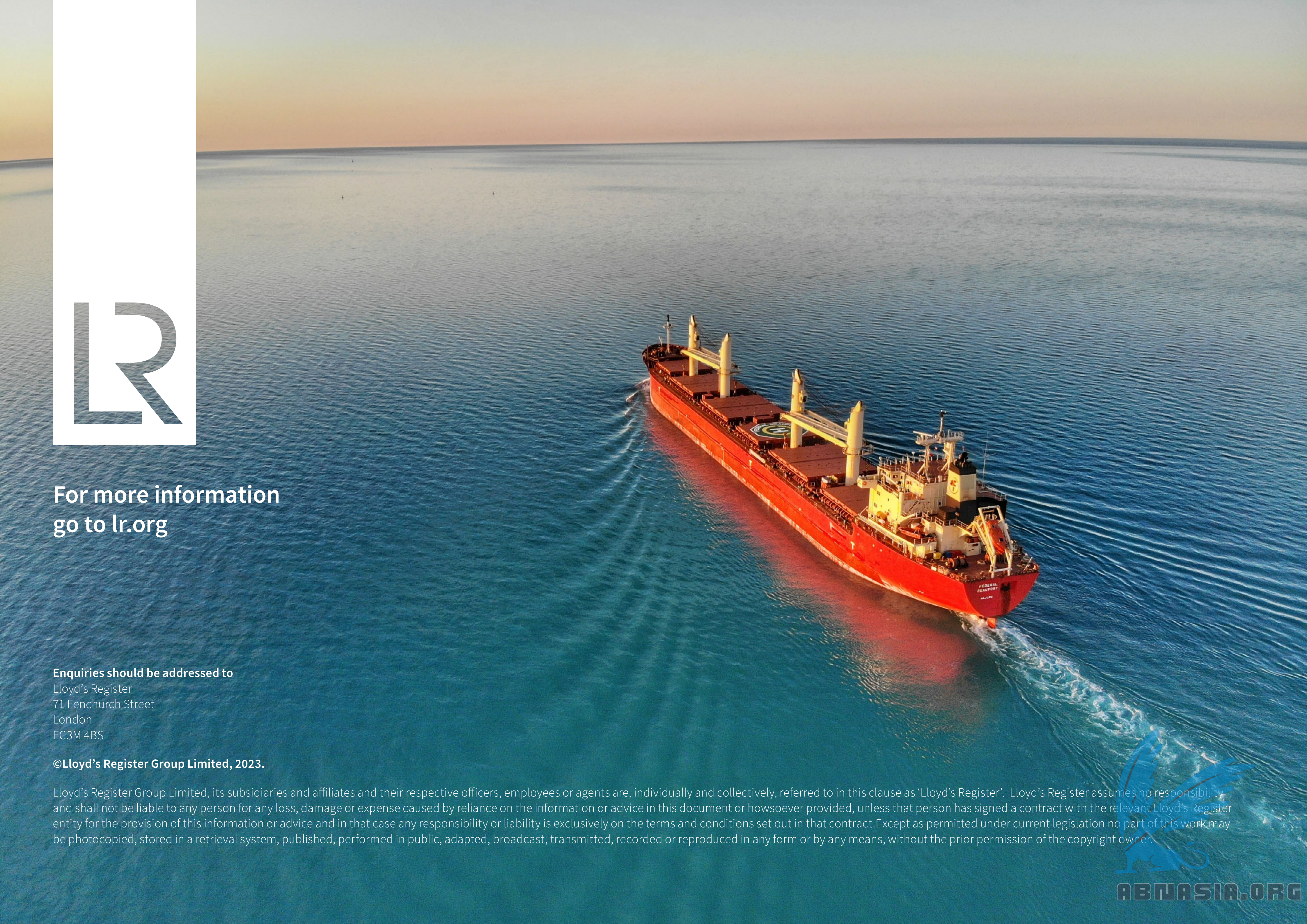
Near-zero refers to the GHG emissions associated with the use of fuels produced using best available technology and 100% renewable energy that achieve overall GHG gas reductions equal to or greater than 80%, but less than 100% when compared to Low-Sulphur Fuel Oil (LSFO) produced through conventional refining methods.

As an example, renewable ammonia would deliver significant tank-to-wake GHG emissions which, combined with minimisation of well-to-tank GHG emissions, could bring lifecycle (well-to-wake) emissions to near zero. Renewable methanol would retain high tank-to-wake GHG emissions which could be reduced to near zero through use of captured carbon and the best available technology across the production and supply chain.

Fuel colours

To more accurately reflect the GHG emissions reduction potential associated with fuels, a colour palette is often used to identify the production process and feedstocks of fuels, which have different impacts on lifecycle emissions. The table below describes the various shades of methanol according to their production process and/or feedstock.

Methanol colour	Other names	Definition focusing upon production
Black	-	The use of coal as a feedstock, considered to the production pathway with highest emissions.
Blue	ng-methanol	Produced from fossil sources (usually coal or gas), but by utilising carbon capture and storage (CCS) the overall CO_2 emissions are greatly reduced.
Brown	-	The same as 'black' above - terms used interchangeably.
Green	Re-methanol, biomethanol and e-methanol	Sustainable electricity (usually wind or solar) is utilised in its producton, emitting the lowest possible CO_2. To be consiered truly green, the production should be carbon-negative either by using biomass or direct air captire (DAC) technology. The most common method for producing renewable methanol is using hydrogen (produced from water electrolysis) ad CO_2 (from DAC) which are then combined using Methanol Synthesis. Biomenthanol is typically produced from lignocellulosic feedstocks (biomass) such as agricultural waste and by-products. E-methanol is typically produced from carbon dioxide (extracted from ambient air using direct air capture (DAC) and green hydrogen.
Grey	-	Has uncontrolled release of CO_2. This production is often based on fossil fuels as raw materials. Usually refers to the use of natural gas which is used to produce syngas, then made into methanol using the Fischer-Tropsch process.
Pink	Red	Produced using nuclear power.
Yellow	-	The same as green methanol but using electricity from the national grid.



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