Zero Carbon Fuel Monitor

Ship readiness for zero carbon fuels

The Lloyd's Register Maritime Decarbonisation Hub

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Executive Summary

The maritime industry's transition to zero or near-zero carbon fuels is advancing across technology, investment, and community readiness dimensions. Significant progress has been made in developing technologies for ammonia, hydrogen, and methanol, with a growing number of vessels being ordered that can run on these cleaner fuels. Additionally, offtake agreements between shipowners and fuel suppliers are becoming more common, particularly for methanol, signalling increased market confidence.

HVO and liquefied methane have reached high readiness levels since HVO, as a drop-in fuel, requires minimal modifications to existing engines, and liquefied methane benefits from established LNG technologies. Ammonia combustion engine technology has been proven in a prototype environment, and hydrogen engines running on 100% hydrogen are starting to enter the market. Advancements in fuel cell technologies are also promising, offering solutions suited to various ship types, fuels, and operational requirements.

However, critical challenges remain. Safety concerns, especially for ammonia, hydrogen and methanol, necessitate ongoing efforts in developing robust safety protocols and crew training. Safety must also be addressed through vessel design to minimise risks to crew. Additionally, regulatory development by the International Maritime Organization (IMO) and its proven application across the industry are essential to ensuring safe and effective adoption.

Technological challenges persist, including mitigating methane slip, achieving continuous ammonia engine operation, and reducing the reliance on pilot fuels. These issues must be addressed to ensure the operational viability of these fuels as zero (or near zero) carbon solutions.

Policy interventions and technological advancements throughout the supply chain are crucial to reduce investment risks at ship stage by ensuring future fuel supply certainty and infrastructure availability. Policy can also be used as an instrument to incentivise investments in these onboard fuel technologies.

Collaboration across the supply chain will be key to overcoming these challenges and achieving a successful transition to cleaner marine fuels.

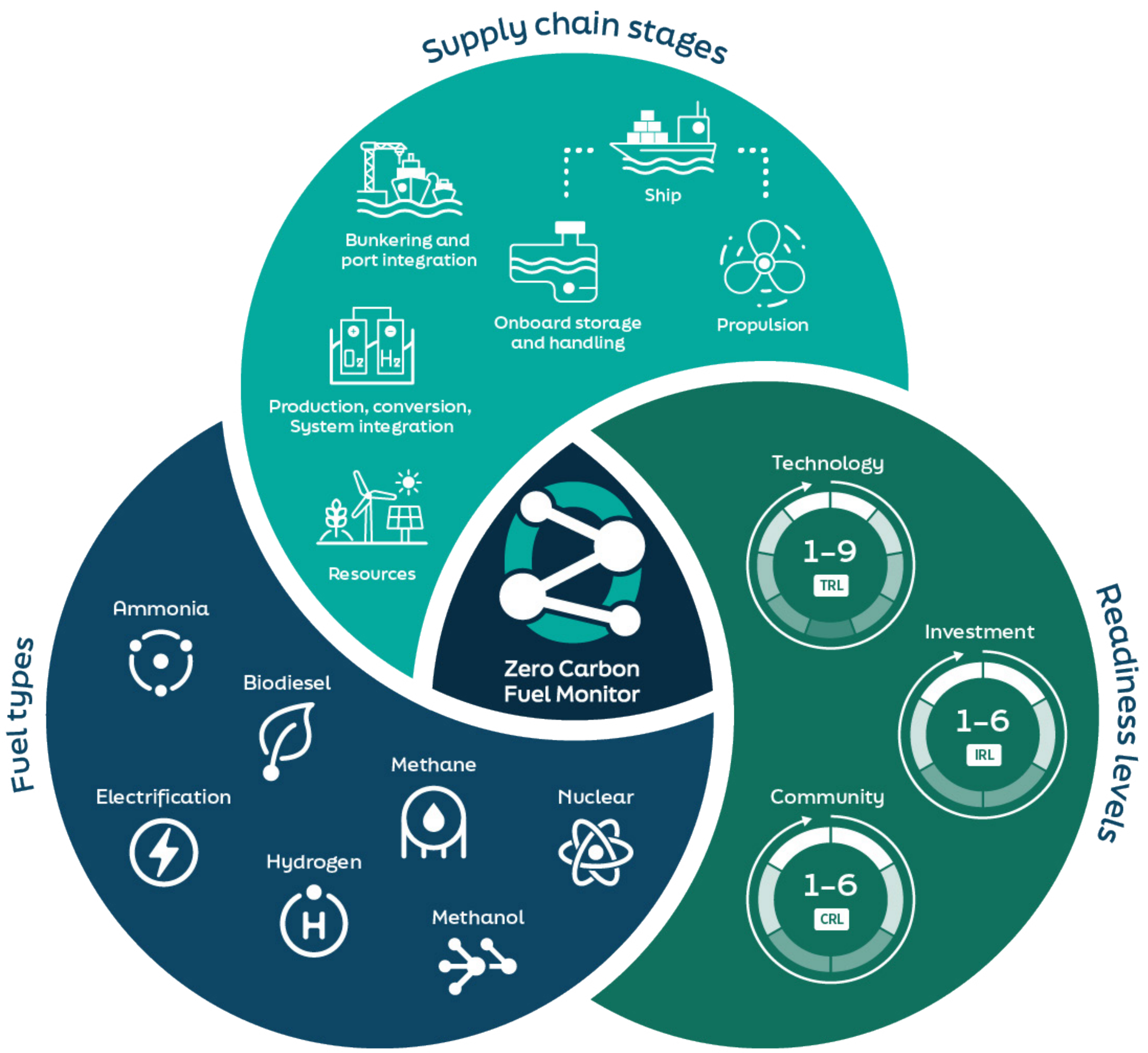
Introduction

The shipping industry is on the brink of a revolutionary shift towards decarbonisation, with several fuel types and technological solutions emerging as alternatives to traditional fossil fuels and systems.

To evaluate the feasibility and readiness of various new fuels and technologies for maritime applications, the Lloyd's Register Maritime Decarbonisation Hub's **Zero Carbon Fuel Monitor (ZCFM)** employs a structured framework assessing technology readiness levels (**TRL**), investment readiness levels (**IRL**), and community readiness levels (**CRL**) across the supply chain.

This update focuses on the final stage of the fuel supply chain, the ship, giving a readiness indication of zero (or near zero) carbon fuel use onboard vessels. Both "handling and storage" and "propulsion" are assessed from a technology readiness perspective, whilst one overall "ship" rating is given for investment readiness and community readiness. The technologies assessed at the "propulsion" stage may also be used to power auxiliary systems. The fuels under consideration in this update are ammonia, biofuels (FAME and HVO) , hydrogen, liquefied methane and methanol.

This update provides a summary of advancements for each of the fuels, as well as highlighting key priorities to be addressed.



Readiness at a glance

The latest update in the Zero Carbon Fuel Monitor (ZCFM) has revealed significant advancements in the state of ship readiness over the last year.

Technology has advanced across all fuels, resulting in considerable increases in technology readiness levels (**TRL**s) over the past year. There has also been a rise in commercial trials and applications. Consequently, the investment readiness levels (**IRL**s) of fuels at the “ship” supply chain stage are increasing. However, **IRL**s at ship stage are still impacted by uncertainties earlier on in the supply chain around future fuel availability and supply infrastructure, as well as the need for policy to incentivise these investments.

Evidence from technology trials and the growing urgency for zero and low carbon fuel uptake is enhancing “ship” supply chain stage community readiness (**CRL**s). However, significant challenges remain, particularly with ammonia, hydrogen and methanol, where safety risks have yet to be fully mitigated. Additionally, fugitive methane emissions from the combustion of liquefied methane still need to be accurately measured and addressed.

	Ship			
Fuel	TRL H&S	TRL P	IRL	CRL
Ammonia	5	6	2	2
Biofuel	9	9	5	5
Biofuel	9	9	5	5
Hydrogen	7	7	2	2
Methane	9	9	5	2
Methanol	9	9	3	3

IRL	Investment Readiness Level
CRL	Community Readiness Level
TRL H&S	Technology Readiness Level - Handling and Storage
TRL P	Technology Readiness Level - Propulsion

The readiness levels rate Technology on a scale from 1 (lowest) to 9 (highest), and both Investment and Community on a scale from 1 (lowest) to 6 (highest).

For more detailed information, including a breakdown of readiness for different technology types, visit the **ZCFM** here.

Overview by fuel type

Ammonia

TRL (handling & storage): 5
Testing prototype in user environment

TRL (propulsion, combustion engine): 5
Testing prototype in user environment

TRL (propulsion, fuel cells): 6
Pre-production product

IRL: 2
Commercial trial, small scale

CRL: 2
Stakeholder support or opposition is becoming understood as a result of pilots

OVERVIEW

Mainstream manufacturers are going through full scale validation testing on ammonia engines, which are now available to order. It should be noted that engines being testing now run on ammonia at high load, switching to fuel oil when approaching and leaving berth. Additionally, a pilot fuel such as fuel oil is needed when the engines are running on ammonia. Engine manufacturers are trying to reduce the use of pilot fuel and N_2O emissions.

Ammonia fuel cells are starting to be deployed onboard vessels, with solid oxide fuel cells representing the most advanced technology in this field.

There are currently 31 “Ammonia Capable” vessels in the existing fleet and on order, and over 400 “Ammonia Ready” vessels. The majority of “Ammonia Capable” vessels are gas and bulk carriers, currently in build which may require significant investment to run on ammonia.

The industry is actively working to identify and mitigate onboard safety risks and crew training needs associated with operating ships using ammonia.

Demonstration of the commercial case for ammonia-fuelled ships, depending on ship type, size and operational profile, will support investment to accelerate technology readiness advancements.

EXAMPLES

Yara Clean Ammonia and North Sea Container Line have announced the “Yara Eyde”, an ammonia fuelled container ship which is due to enter service from 2026, operating between Norway and Germany.

Combustion engines

- Fortescue’s “Green Pioneer” vessel is the first example of proving ammonia combustion engine technology in a prototype environment. The proof-of-concept vessel has had two of the four engines converted to enable it to run in dual-fuel mode on ammonia and diesel.
- In Japan, the “Sakigake” tugboat has been been converted to an ammonia-fuelled vessel by NYK and IHI Power Systems in cooperation with ClassNK. This will now be employed in tugboat operations in Tokyo Bay for a 3-month demonstration period.

Fuel cells

- H2POWER technology have received an AiP from LR for H2SITE’s AMMONIA for ammonia cracking on-board. The hydrogen can then be utilised by hydrogen fuel cells. These fuel cells are already in use on a near-shore supply vessel off the coast of Spain.
- LR has awarded an AiP to Samsung Heavy Industries (SHI) and Amogy for an 88,000 cbm fuel cell-powered ammonia carrier, which uses ammonia cracking to create hydrogen for the fuel cell stored onboard. Amogy’s technology has now been deployed on the “NH_3 Kraken” tugboat, which previously ran on diesel.

Onboard safety

- Building on the LR Maritime Decarbonisation Hub and Mærsk Mc-Kinney Møller Center Recommendations for Ammonia-Fuelled Vessels report, a Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping report has been published. This report provides an assessment of eight human factors impacts and outlines recommended priorities for lowering the risks of ammonia as a shipping fuel.

Biofuel (FAME)

Fatty Acid Methyl Esters

TRL (handling & storage): 9
Production and product fully operational

TRL (propulsion): 9
Production and product fully operational

IRL: 5
Market competition driving widespread development

CRL: 5
Increased transparency and formalised processes driving momentum for change

OVERVIEW

There are a number of vessels now running on B100 Fatty Acid Methyl Esters (FAME) (100% biodiesel), which can be considered near net-zero if the carbon released during vessel operation is sufficiently offset by the carbon absorbed by the resources used for fuel production.

Since biodiesel is considered a 'drop-in' fuel (i.e. no, or little, modification required, only adjustments), the technology and infrastructure investments are minimal and pose low risk.

IMO MEPC 80 approved MEPC.1/Circ.905 Interim guidance on the use of biofuels under regulations 26, 27 and 28 of MARPOL Annex VI, which incorporates current lifecycle analysis formulae as defined by independent sustainability certification. This guidance sets the well-to-wake GHG emissions reduction level at 65% of fossil marine gas oil and has encouraged uptake of biofuels, although still primarily as blends. The interim guidance will be rescinded immediately upon operationalisation of a well-to-wake GHG methodology through the IMO LCA guidelines.

Since this is an evolving market and the LCA emissions reduction level has now been defined as 65% in these guidelines, we will re-consider our definition of "near zero carbon fuels" to determine whether FAME is included in the ZCFM assessment in the future.

ISO have now updated the ISO 8217 marine fuel standard to include FAME fuels up to 100%.

Uncertainties around the availability of FAME will impact the uptake of this biofuel, although the technology is in place to use it.

EXAMPLES

Canada Steamship Lines have achieved 75,000 hours over the past 4 years, with eight vessels currently running on B100.

Biofuel (HVO)

Hydrotreated Vegetable Oil

TRL (handling & storage): 9
Production and product fully operational

TRL (propulsion): 9
Production and product fully operational

IRL: 5
Market competition driving widespread development

CRL: 5
Increased transparency and formalised processes driving momentum for change

OVERVIEW

Hydrotreated Vegetable Oil (HVO), also sometimes referred to as Hydro processed Esters and Fatty Acids (HEFA) is considered a 'drop in' fuel as it is indistinguishable from petroleum gas oil, and therefore no (or minimal changes) are required onboard.

The cost and availability of the fuel is limiting uptake for ocean going vessels, although there are a few commercial applications.

Another possible application for HVO in a (near) zero carbon solution is as a pilot fuel for ammonia or methanol.

EXAMPLES

Commercial applications of HVO include use by Svitzer in their UK tugboat fleet.

Hydrogen

TRL (handling & storage for compressed gas, liquid organic hydrogen & liquid hydrogen): 7
Low scale pilot production demonstrated

TRL (propulsion, combustion engine): 6
Pre-production product

TRL (propulsion, fuel cells): 6
Low scale pilot production demonstrated

IRL: 2
Commercial trial, small scale

CRL: 2
Stakeholder support or opposition is becoming understood as a result of pilots

OVERVIEW

During the onboard handling and storage stage, pilot projects have been initiated for liquid, liquid organic, and compressed gas systems.

Engines that run on 100% hydrogen currently exist and are starting to enter the market although potential challenges with include controlling levels of hydrogen slip and NO_x. Meanwhile, fuel cells have been proven effective and are actively being used by near shore first movers, although only on specific routes and under certain conditions.

There are currently 78 "Hydrogen Capable" vessels in the existing fleet and orderbook. Applications of hydrogen for propulsion are limited to smaller, near-shore cases, with the majority being coastal ferries and support vessels.

The overall ship readiness, if assessed for larger ship types only (such as ocean-going containerships), would be lower. This is because the practicalities of these solutions for such ship types may affect operating patterns (e.g. more frequent bunkering) or cargo carrying capacity.

Work is ongoing across the industry to identify and mitigate the safety risks posed by operating ships using hydrogen.

EXAMPLES

Combustion engines

- LR has awarded the first Type Approval to 'BeHydro', a joint venture between CMB.TECH and Anglo Belgian Corporation (ABC), for its hydrogen-powered dual-fuel engine. These engines are currently operational in the Hydrotug 1 tugboat, serving the Port of Antwerp-Bruges.
- MAN Energy Solutions' licensee, MITSUI E&S Co. Ltd., has set a groundbreaking milestone in the maritime industry by successfully testing a 50-bore MAN B&W two-stroke engine at full 100% load using hydrogen fuel. This achievement marks a world-first in the sector.

Fuel cells

- Norled's MF Hydro liquid hydrogen-powered ferry is now approved for service and operational.
- Future Proof Shipping (FPS) in the Netherlands has launched H2 Barge 2, a hydrogen-powered vessel transporting goods on the Rhine. This uses liquid organic hydrogen carriers and battery packs for clean and efficient energy.
- SWITCH Maritime is launching commercial operations of its compressed gas hydrogen-powered catamaran ferry, Sea Change, in San Francisco.
- This year, Feadship's Amsterdam shipyard launched a superyacht which is powered by a combination of hydrogen fuel cells (with the hydrogen stored in liquid form) and HVO biofuel.
- Torghatten Nord has ordered two hydrogen-powered ferries, each 117 meters long with a capacity of 120 cars, to operate between islands in Norway. Featuring advanced fuel cell technology, these vessels will be the largest hydrogen-powered ferries in the world once completed.

Liquified methane

TRL (handling & storage): 9
Production and product fully operational

TRL (propulsion): 9
Production and product fully operational

IRL: 2
Commercial trial, small scale

CRL: 2
Stakeholder support or opposition is becoming understood as a result of pilots

OVERVIEW

The technology for handling, storage, and combustion engines using liquified methane is fully operational and proven with LNG. This technology is directly transferrable to pure liquified e-methane and bio-methane.

However, fugitive emissions from storage and methane slip during combustion remain a challenge. Ongoing efforts aim to refine the technology to eliminate or significantly mitigate methane slip through initiatives such as the Methane Abatement in Maritime Innovation Initiative (MAMII).

Methane fuel cell technology – both Solid Oxide Fuel Cells (SOFC) and Proton-exchange membrane fuel cells (PEMFC) – have been developed and are being tested by manufacturers. SOFC technology is currently more mature due to being used with natural gas as a fuel in stationary power plant applications.

The primary barrier to the adoption of pure liquified e- and bio-methane is the lack of a compelling investment case and limited availability. However, the technology for these fuels is identical to that used for LNG, and therefore the technology is already attracting substantial investment.

EXAMPLES

The Methane Abatement in Maritime Innovation Initiative (MAMII), led by LR's SafetyTech Accelerator, is exploring technologies to monitor, measure and mitigate methane slip emissions. The initiative will provide actionable recommendations to enable immediate steps in reducing methane emissions across fleets.

In a technological step towards enabling high methane slip reductions, Daphne Technology's SlipPure™ wavelet pulse power supply technology has been awarded an AiP by LR, with 62% methane slip reduction at 75% load.

Solid Oxide Fuel Cells already deliver some of the power required onboard the MSC World Europa cruise ship using LNG, although the technology is also compatible with e- and bio-methane, as well as other (near) zero carbon fuels.

Methanol

TRL (handling & storage): 9
Production and product fully operational

TRL (propulsion): 9
Production and product fully operational

IRL: 3
Commercial scale up

CRL: 3
Early stage solution formation to tackle stakeholder issues

OVERVIEW

Materials and components for onboard storage are already in use. Engines have been successfully demonstrated and applied in deep sea methanol carriers and fuel cell technology has been tested, with pilot projects in planning.

Technology has been deployed on 315 "Methanol Capable" vessels, with nearly 500 vessels classed as "Methanol Ready" in the existing fleet and orderbook. However, many vessels that run on methanol are using blue methanol, which is currently more widely available.

Commercial trials are on the rise, and offtake agreements between shipowners and fuel suppliers are becoming more common, however scalability of e- and bio-methanol remains an issue.

Regulations for methanol-fuelled ships are already established, although the risks related to toxicity and flammability are not yet widely understood.

EXAMPLES

Combustion engine

- The Laura Maersk vessel is now in operation running on methanol, with a fuel supply secured by Maersk and more methanol-fuelled vessels on order.
- Additionally, Stena Lines and LR are working on a project to retrofit two fast roll-on/roll-off vessels (Stena Superfast VII and Stena Superfast VIII) with methanol propulsion. These will be dual-fuel vessels, building on the successful conversion of the Stena Germanica vessel conversion to methanol in 2015.

Priorities to increase readiness

A major limiting factor in the adoption of new fuels is the lack of positive investment cases. Shipowners are still confronting significant uncertainties throughout the supply chain, including fuel supply, port infrastructure, safety requirements, and regulatory frameworks. Additionally, the current operational cost gap needs to be addressed through financing and policy changes to make zero and near-zero carbon fuel solutions commercially viable for shipowners. The priorities outlined below will contribute to increasing ship readiness to adopt zero (or near zero) carbon fuels.

PRIORITY AREA

Future fuel supply and infrastructure

A key factor in vessel investment decisions is confidence in future supply of fuel. To reduce uncertainties and accelerate investment decisions at the "ship" stage, stakeholders across the entire value chain must work together to create supply chains for future zero (or near zero) carbon fuel uptake.

STAKEHOLDER ACTIONS

- **Stakeholders across the supply chain** can form green corridor clusters, such as the Silk Alliance, to create and define regional demand. This type of collaboration will help reduce investment risks in supply, infrastructure, and fleet for each member. Additionally, it will facilitate coordinated action on financing and policy changes.
- **Governments** must actively engage stakeholders across the entire energy value chain to identify opportunities and key collaborative actions that will accelerate fuel supply development. This approach will help mitigate risks associated with zero-carbon fuel vessel investments. An example of this is the Maritime Fuel Supply Dialogues, an LR Maritime Decarbonisation Hub initiative bringing together energy and transport ministries across Asia Pacific and Africa.
- To increase investment readiness in onboard ship technology for methanol, scalability of fuel supply still needs to be demonstrated. The challenges in scaling e- and bio-methanol supply are due to uncertainties around biogenic sources of carbon, and the need for lower energy intensity, lower cost Direct Air Capture technology. **Governments** could provide targeted funding and subsidies for research and development in DAC technology and sustainable biogenic carbon sourcing for methanol production. Additionally, offtake agreements for e- or bio-methanol between **shipowners** and **fuel suppliers** will help to provide a secure demand that justifies investment in scale-up.
- Sustainable scale-up of feedstock for biofuels for shipping use is needed for increased adoption. **Research institutions** (with support from **governments**) could direct efforts into the development of technology and practices for farming of resource-efficient, high yield, sustainable feedstocks, that could be located practically to produce marine biofuels.

PRIORITY AREA

Safety considerations

Hazards introduced by adopting zero (or near zero) carbon fuels need to be fully understood and the risk mitigations identified (e.g. through various risk assessment methodologies such as the Quantitative Risk Analysis). New crew safety regimes are needed, the training sector must gear up to deliver and operators must adopt new ways of working.

STAKEHOLDER ACTIONS

- **Research coalitions** can conduct controlled testing to validate hypotheses regarding fuel characteristics. For instance, the SAFEN joint industry project has been launched to enhance our understanding of hydrogen ignition mechanisms through a comprehensive experimental campaign. Additionally, investigating the impact of ammonia spills in water has been identified as a crucial area for further study.
- Real world trials need to be conducted by **shipowners / operators** to practically implement safety mitigations, such as PPE requirements.
- There is ongoing work such as the United Nations Global Compact (UNGC) Maritime Just Transition Taskforce (MJTTF) programme to create a baseline training framework for seafarers for ammonia, hydrogen and methanol. The Maritime Energy Training Facility (METF) has also recently been established by the MPA in Singapore to address the current competencies gap. This momentum needs to be maintained by **training institutions and coalitions throughout the industry** to ensure that the workforce is prepared to handle new fuels onboard safely.
- The **IMO** needs to amend the STCW framework to further develop the minimum training requirements for ammonia, hydrogen and methanol. In parallel, **industry crew training centres** need to develop training materials to respond to industry demand rather than regulation, to avoid delays whilst the STCW framework amendments are being defined and published. Examples of such initiatives include the METF, and the recently announced collaboration between MAN and Eastern Pacific Shipping for ammonia training.
- **Technology providers** and **ship designers** need to work together to create human-centred designs when integrating technology for new fuels onto ships. Additionally, opportunities to enhance safety through new technologies such as automation need to be explored, as well as the implications they may have on other areas such as training.

PRIORITY AREA

Technology trials

Technology development, trials and scale-up need to continue at pace. Evidence from technology trials will diminish uncertainties in operation, thereby further supporting advancement of investment and community readiness.

STAKEHOLDER ACTIONS

- **Shipowners and partners** need to start investing in trials with **technology providers** that widely demonstrate the capability and reliability of ammonia, hydrogen and methanol technologies.
- The technology required to monitor, measure and mitigate methane emissions needs to be proven by **technology providers** and adopted by **shipowners**. MAMII provides a means to explore and endorse scalability technology solutions.
- Policy intervention that will unlock the economic feasibility of investing in cleaner fuels at ship stage is needed, which will ultimately unlock investment to accelerate technology readiness. **Governments** and **regulatory bodies** could introduce such incentives and establish clear regulatory frameworks that mandate or encourage adoption of zero (or near zero) carbon fuels.

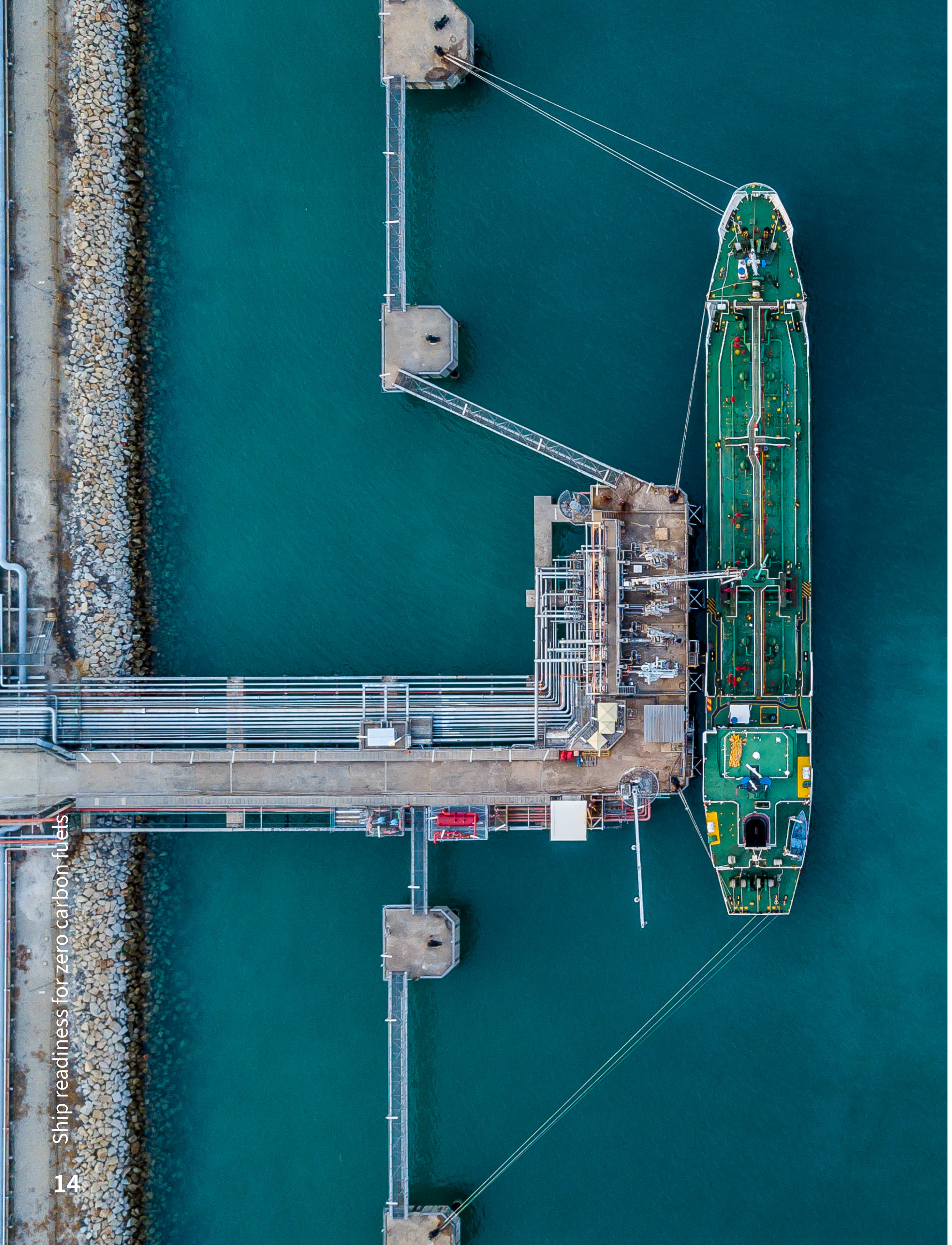
PRIORITY AREA

Policy and regulation development and application

The regulatory landscape poses significant challenges for operating ships powered by ammonia and hydrogen, while methane emissions are not yet measured and regulated. It is crucial for policy to be stable and consistent across the value chain, and on a global scale.

STAKEHOLDER ACTIONS

- Development of requirements by **regulatory bodies and international organisations** such as Fuel EU maritime will drive the uptake of alternative fuels.
- The primary challenge in adoption of regulations and standards will be to effectively communicate the established safety standards and demonstrate compliance to all stakeholders. This is essential to minimise variation in interpretations and additional regional requirements that could create obstacles for shipowners. Stakeholders responsible for approval of alternative and/or equivalent designs, i.e. **flag states**, could be required to increase competence and capacity as well as standardise processes to ensure that the industry safety standards are achieved consistently and effectively.
- Interim guidelines for the safety of ships using ammonia have been finalised at the **IMO** and are expected to be approved during MSC 109 in December 2024. These were developed using the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF). Further development to these guidelines will be needed once experience in their use has been gained. It is anticipated that such guidelines for hydrogen will be finalised in 2025
- Although methane (natural gas) is a normative gaseous/ low-flashpoint fuel, its methane emissions when used in internal combustion engines are not yet regulated. The **IMO** plans to publish regulations on methane emissions, which will increase confidence in liquified methane systems.



Summary

As the industry moves forward, technology capabilities in fuel handling, storage and propulsion onboard vessels are being developed further, and work is in progress across the industry to address challenges related to the adoption of zero and near zero carbon fuels. This is crucial for advancing the readiness of ships for these fuels in the journey to decarbonisation.

The **ZCFM's** insights serve as a valuable resource for stakeholders across the maritime sector, including providing a detailed snapshot of vessel readiness for each fuel type. Evaluating their potential to contribute to a sustainable maritime future, emphasising current strengths and pinpointing areas requiring further development and investment. This evaluation showcases the trajectory of these fuels towards becoming key components of the industry's decarbonisation strategy.

Find out more about the **Zero Carbon Fuel Monitor (ZCFM)** here.

Maritime Decarbonisation Hub

Get in touch

www.maritimedecarbonisationhub.org

To find about more information please visit: **www.lr.org/zcfm**

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