GETTING TO ZERO COALITION
GLOBAL MARITIME FORUM

From pilots to practice: Methanol and ammonia as shipping fuels

August 2025

Executive summary

Since 2020, the *Mapping of Zero-Emission Pilots and Demonstration Projects* has provided an overview of the nature and scale of zero-emission pilots and demonstration projects in shipping. To keep pace with developments in the sector, this year's edition takes a new approach and assesses the current status of methanol and ammonia as shipping fuels.

Methanol and ammonia have not yet been widely adopted in shipping, but are expected to have a large potential role in the sector's decarbonisation. As these fuels cannot be "dropped in" to existing infrastructure, they require the coordinated development and deployment of new land- and sea-based technologies. This means that piloting and demonstration—and the subsequent steps needed to develop a mature supply chain—are of particular importance.[1]

The findings focus on ships and bunkering, with fuel production developments not treated in depth, since they are well-addressed by other publications and benefit from a wider frame of analysis, that covers the broader energy system. Insights are sourced from interviews with around 40 companies and organisations that have invested in methanol or ammonia assets or are involved in relevant research and demonstration projects. While the organisations interviewed represent a meaningful share of activity, their learnings may not necessarily be true for other early adopters and may change as more evidence emerges. As such, the findings should be considered a snapshot of progress in mid-2025.

Meanwhile, the report introduces a new framework for assessing the maturity of scalable zero-emission fuels, breaking down the "emergence phase" of shipping's transition into three sub-stages: 1) Proof of concept, reached once a fuel has been shown to be safe and effective in real-world demonstrations; 2) Initial scale, reflecting small-scale commercial adoption of the fuel on specific routes and ports; and 3) Maturity, marking the fuel's development into a widely available solution, with limited barriers to uptake.

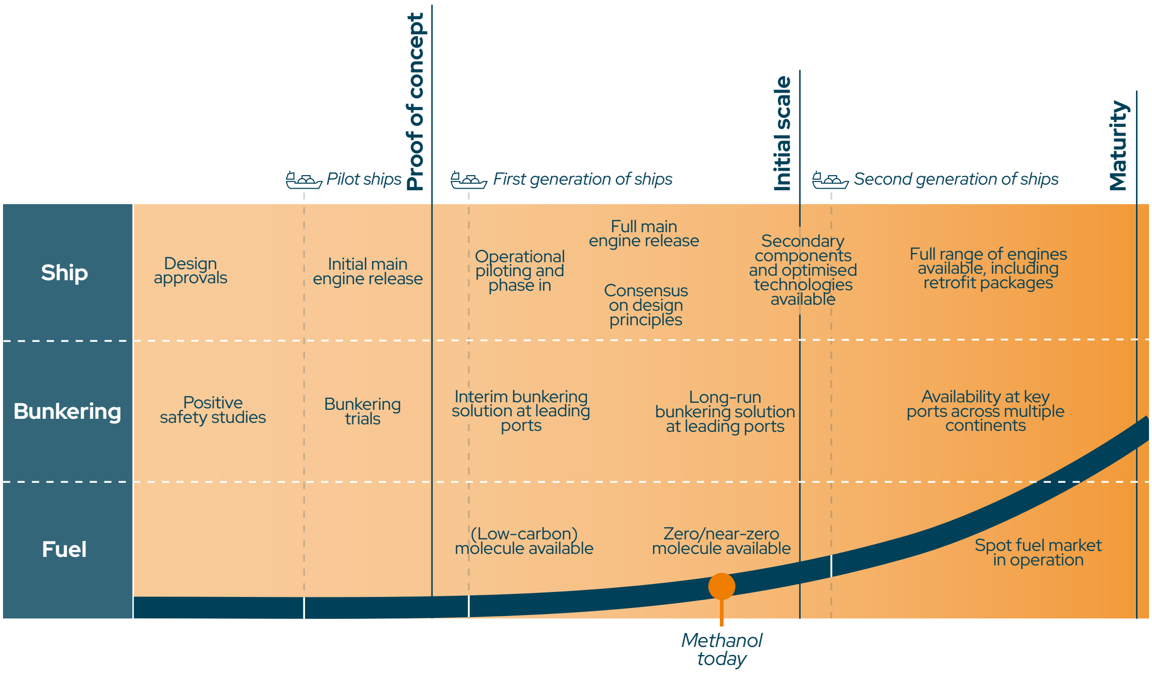
1 Fuels such as e-diesel and e-methane, which are potentially scalable as they use electrolytic hydrogen as a feedstock, can be dropped into existing infrastructure and as such are not the focus of this report

Methanol

Methanol is past proof of concept and moving towards Initial scale, with around 60 methanol-capable vessels on the water, more than 300 further ships on order, and just under 20 ports offering green methanol bunkering at the time of writing.

Design and technology

Figure 5: Estimated maturity of methanol as a shipping fuel in mid-2025



Source: Global Maritime Forum assessment, based on stakeholder insights and Clarkson's World Fuel Register data

Early movers are finding methanol relatively easy to adopt, thanks to its liquid state at room temperature and pressure, and the availability of key components such as engines, fuel tanks, and supply systems.

While fuel and bunkering systems on the ships generally work well, early movers report encountering teething problems with the engine and sourcing spares and parts. Engine designers are addressing both issues, and solutions are expected to be available soon.

Methanol's lower energy density than conventional fuel leads to trade-offs between endurance, frequency of bunkering, and capital expenditures (CAPEX). These trade-offs are being handled in different ways and have not proven to be a significant barrier, with methanol-powered ships able to complete even long voyages, albeit bunkering around twice as frequently as conventional ships.

Meanwhile, the first retrofit projects suggest that, while a significant undertaking, retrofitting ships to methanol should not only be feasible, but potentially practical. Retrofitting conventional ships to use methanol is expected to be cheaper than retrofits for other alternative fuels, due to relative limited changes being required to the engine and tanks, and engine retrofit packs soon to be available. However, the timeline, upfront cost, and yard capacity for completing methanol retrofits should be improved to support wider take-up.

Operation and bunkering

In terms of operations, risk assessments performed by leading ports show that methanol requires the lightest precautions of the main alternative fuels and bunkering is relatively similar to fuel oil. The ability to use conventional bunker barges with limited modifications and positive perceptions about the fuel among port workers, terminals, and wider port stakeholders have helped accelerate the rollout of methanol bunkering, which is available at 42 ports at the time of writing.

These positive perceptions are shared by seafarers. While a bottleneck in the availability of methanol training developed over the past few years, this has now been passed, with an ecosystem of training providers available to upskill crews.

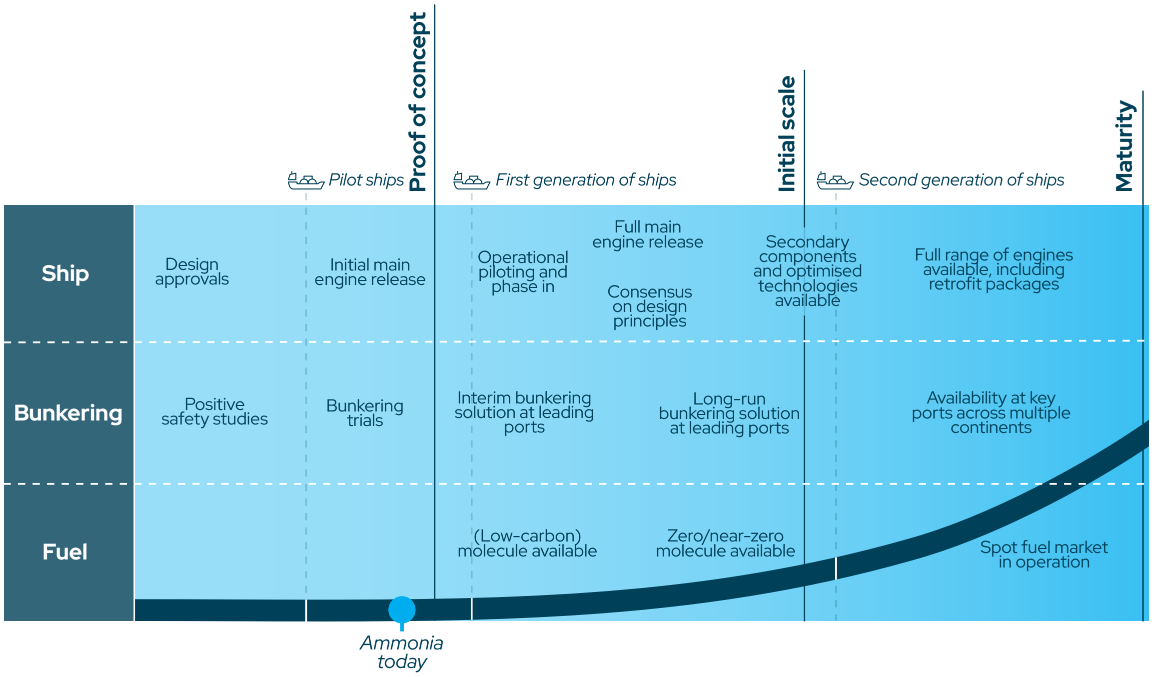
The main hurdle to further maturation and scale-up of the fuel is the availability of green methanol molecules. Most methanol used on ships to date has been grey methanol,[2] with only small volumes of bio-methanol being bunkered since 2023 and the first volumes of e-methanol being bunkered in May 2025. Sufficient supply of green methanol is available, particularly in China, but it is costly and must be accessed through long-term offtakes, which remain problematic.

Ammonia

Meanwhile, ammonia is rapidly approaching proof of concept as a shipping fuel, with the first ammonia-powered vessels successfully piloted, engine testing near completion, and bunkering trials underway at major ports. Critical knowledge gaps are being filled, including in the key areas of safety, emissions, and bunkering.

2 Green methanol refers to methanol with very low to zero production emissions, including e-methanol (produced using hydrogen from renewables-based water electrolysis and sustainable carbon) and bio-methanol (produced using waste or residual biomass feedstocks). Grey methanol refers to conventional methanol produced from unabated natural gas.

Figure 9: Estimated maturity of ammonia as a shipping fuel in mid-2025



Source: Global Maritime Forum assessment, based on stakeholder insights and Clarkson's World Fuel Register data

Safety and design

Interviews with shipowners and operators suggest that significant changes are needed in the design of safe ammonia-powered ships to effectively manage the fuel's toxicity. This includes segregating sections for leak management and a package of safety measures and technologies, such as extra gas detectors, automatic shutdown, double-wall piping, water sprays, and refrigeration. These measures and technologies are not new, but understanding how to best integrate them has been a major focus.

The training of crews to operate the first wave of ammonia-powered vessels is also underway, with facilities such as the Alam Maritime Academy in Malaysia and Anglo-Eastern Maritime Academy in India in the process of training hundreds of seafarers. Life on board is expected to be broadly similar for most crew members, albeit more complex, particularly for those in the engine room, involved in bunkering, and first responders.

Operators have received mixed reactions from seafarers about the prospect of working on these ships, ranging from them actively volunteering to expressing hesitations. However, seafarers are generally becoming more comfortable with the idea of handling ammonia as they become more familiar with the molecule.

Emissions

While ammonia does not contain carbon, it can produce other emissions when burnt, including the potent greenhouse gas nitrous oxide and ammonia slip. High levels of either could represent a showstopper for the fuel.

The levels of these emissions have until recently been unclear, but results from full-scale engine tests suggest that operating on ammonia could reduce a ship's tank-to-wake emissions by between 90 and 95%. This exceeds the leading engine designers' own initial expectations and targets. Data from real-world operations is now needed to confirm this picture. Independent measurement would help build confidence in ammonia's expected greenhouse gas footprint.

90-95%+ TTW emissions reduction seems possible when using ammonia

	High load	Low load
N2O	**~1%** fuel oil emissions	**<2%** fuel oil emissions
Pilot fuel	**~5%** energy	**~7%** energy

At the same time, interviewees stress that the introduction of ammonia will be gradual, emphasising that the process is "a marathon, not a sprint". Operators suggest they will initially only use ammonia 25% to 50% of the time on the first ships to build up experience and test systems before considering higher usage levels. The first ammonia-capable ships are also not expected to use ammonia when manoeuvring or at port, and questions remain about when or whether this will happen. Further, blue ammonia is expected to be a common choice through to 2030 at least. Therefore, ammonia-powered ships are unlikely to reach 90 to 95% emissions reductions overnight.

Bunkering

Finally, ammonia bunkering trials are now underway, with multiple trials having been successfully completed. While ship-to-ship ammonia bunkering is yet to occur, the trials have generated early best practices and validated the regulatory framework for future ship-to-ship ammonia bunkering at a handful of leading ports.

Figure 12: Overview of ammonia transfer and bunkering trials completed as of mid-2025

Sources: Global Maritime Forum compilation, based on desktop research

Despite this progress, interviewees agree that bunkering is currently the weakest link in the ammonia value chain. The key gap is infrastructure. There are differences in opinion about what form the infrastructure for ammonia bunkering must take, with some indications that dedicated ammonia bunker vessels may be required from early in the fuel's adoption. Early adopters also note that the knowledge levels and risk appetite for ammonia bunkering differ markedly between ports and terminals, and successful introduction of ammonia bunkering will require timely and proactive engagement between operators, the port ecosystem, and local communities.

Conclusions and recommendations

This report finds that both fuels are now ready—methanol for low-carbon operation and ammonia for piloting. This represents a significant increase in maturity since the release of the first Getting to Zero Coalition Mapping of Zero-Emission Pilots and Demonstration Projects in 2020.

At the same time, it is clear that both fuels require a concerted push if they are to be able to rapidly scale from around 2030 in line with the industry's decarbonisation targets.

The key area that must be addressed is the fuel supply chain. For methanol, this entails enhancing the availability of green molecules; for ammonia, validating and rolling out commercial ammonia bunkering at key ports is now needed. Early movers propose a mix of actions to accelerate the development of the fuel supply chain:

1. **Provide policy incentives to reduce the cost gap facing the fuels**, particularly their e-fuel variants, and support early movers.
2. **Establish robust, harmonised fuel certification** to enable investment in fuel production and validate the fuels' greenhouse gas reductions.
3. **Use book-and-claim systems**[3] to channel global demand for zero-emission shipping while making zero-emission fuel physically available on the most feasible routes.
4. **Operationalise fuel demand aggregation** to provide the level of utilisation needed to justify investments in bunkering infrastructure.
5. **Offer CAPEX grants for bunkering infrastructure** to lower the threshold for investment, particularly in bunker vessels.
6. **Pursue deeper collaboration between ports, terminals, and early movers** through green corridor initiatives, route-based feasibility studies, and/or collaborative bunkering demonstrations, to smooth the introduction of bunkering at relevant ports.

To keep technology and design developments on track, while ensuring safety and climate benefits, they suggest the following additional actions:

1. **Close gaps in the availability of methanol and ammonia engine sizes and types**, particularly auxiliary engines and spare parts, while implementing learnings from methanol and ammonia-powered ships on the water to optimise technologies and reduce costs.
2. **Ensure IMO's life cycle emissions guidelines are robust** with respect to the sustainability of biomass feedstocks and fugitive emissions/slip, including nitrous oxide emissions.
3. **Undertake independent studies to measure the real-world emissions** from the first wave of commercial ammonia-powered vessels.
4. **Enhance knowledge sharing** by, for example, shipyards bringing together shipowners in collaborative risk assessments and marine insurers positioning themselves as knowledge hubs for methanol and ammonia safety.

3 Book and claim refers to a chain of custody system which allows the emission profile of a zero-emission fuel to be separated from the physical flow of that fuel in a transportation supply chain.

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This report has grown from the Getting to Zero Coalition report series, Mapping of zero-emission pilots and demonstration projects that was first published in August of 2020.

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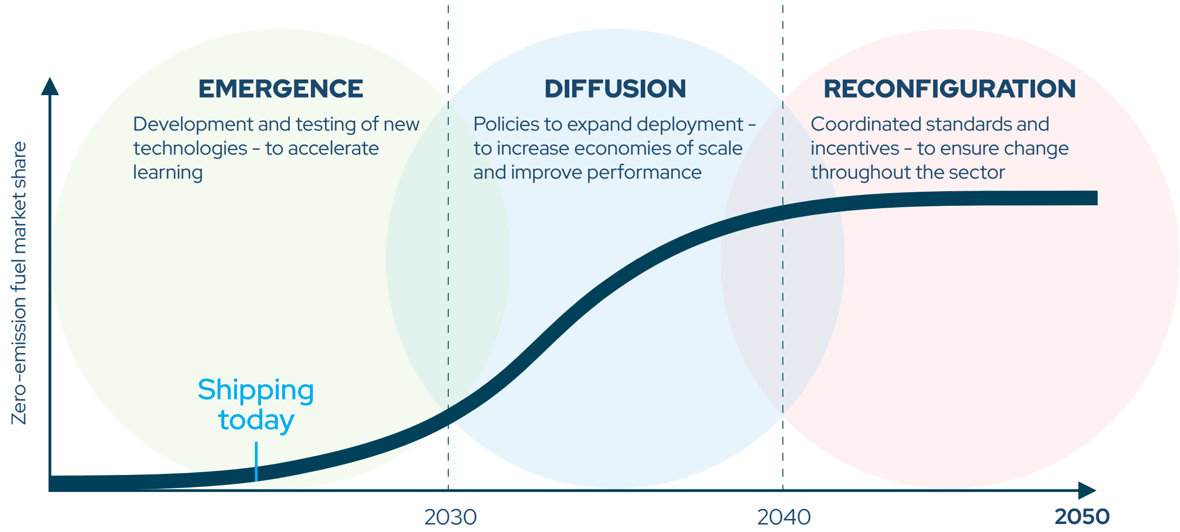
Introduction

Shipping's transition to zero-emission fuels

In 2021, the Getting to Zero Coalition and UN High Level Climate Champions suggested that shipping's transition to zero-emission fuels and technologies would likely follow an S-curve.

Evidence from past transitions in different sectors shows that the adoption of new technologies often follows an S-shaped pattern, in which an initial period of slow uptake (*emergence*) is followed by a rapid increase (*diffusion*), before eventually flattening out (*reconfiguration*).

Figure 1: Shipping transition curve



Source: Adapted from the Getting to Zero Coalition Transition Strategy

This dynamic is the result of mutually reinforcing effects such as learning curves, economies of scale, and network effects, which make new technologies scale rapidly after a certain tipping point in their use is reached.

The tipping point for zero-emission fuels in shipping is estimated to be roughly five percent of the industry's total fuel use. Achieving this level of uptake should mean that the fuels are affordable, available, and attractive enough for large-scale adoption thereafter.

The current consensus in the sector is that methanol and ammonia could be scalable zero-emission fuels that follow an S-curve, particularly if produced with green hydrogen. Other solutions may also fit this profile.

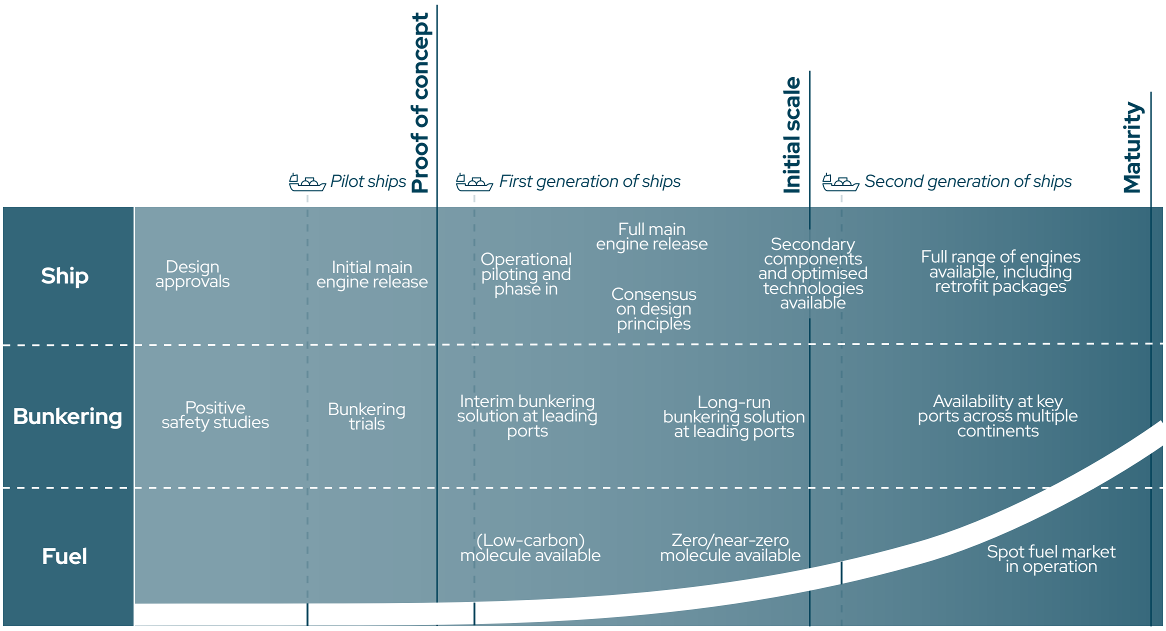
Conceptualising the maturity of methanol and ammonia as shipping fuels

Different frameworks exist for assessing the readiness of methanol and ammonia, including Technology and Commercial Readiness Levels, and qualitative assessment frameworks.

This report introduces a new framework for assessing the maturity of scalable zero-emission fuels, based on the sector's transition curve. It conceptualises the maturation of new zero-emission fuels taking place in three stages. They are proof of concept, reached once a fuel has been shown to be safe and effective in real-world demonstrations; Initial scale, reflecting small-scale commercial adoption of the fuel on specific routes and ports; Maturity, marking the fuel's development into a widely available solution, with limited barriers to uptake. Since ships depend on a fuel supply chain, action across ships, bunkering infrastructure, and fuel production is required to progress through these stages.

The diagram below depicts an idealised version of this journey and a selection of the key actions along the way. The progress of the new fuel through the stages determines its maturity level.

Figure 2: Journey towards technology tipping point in shipping



Source: Global Maritime Forum compilation based on stakeholder insights, IAPH Port Readiness Level tool, The First Wave report, and The Next Wave report

Ship development

The development of innovative ships relies on parallel developments in ship design and technology.

It starts with ship design. This is undertaken on an alternative design approval basis, which involves risk assessments to establish that innovative ship designs meet equivalent levels of safety to existing ships. Once a design has received approval, the vessel can then be constructed. Generally, for the first demonstrator ships able to use a new fuel, this will mean a retrofit.

The main technologies required for implementing a new fuel on a ship are the engine and the fuel supply system. Engine manufacturers will develop and test a design concept in laboratory conditions before building and testing a commercial engine in a testbed. Once testing is successfully completed, the engine will then generally be given a limited release. It will be installed on a first generation of newbuild ships, where the engine and design are tested in real-world conditions. The experience and data gained will then be used to finalise the engine design, enabling a full sales release and generating a level of convergence on the principles and requirements for designing ships using the fuel. This paves the way for a second generation of vessels, which will be optimised and may feature additional technologies that were not available to the first generation. This dynamic is the root of the technology risk many first movers face.

While the first generation of ships is likely to include a limited number of ship types—for example, green fuel carriers and ships with regular operational profiles[4]—the technology will be adopted by a wider range of ship types over time, which requires more engine sizes to become available as well as commercial retrofit packages. At this point, the ship element reaches maturity.

Bunkering development

Bunkering capability is developed gradually, in connection with ship developments.

The process begins with safety studies and risk assessments, such as HAZID (Hazard Identification) and HAZOP (Hazard and Operability Study) exercises, to understand the risk profile of the fuel, identify necessary safety measures, and determine the best locations for bunkering to take place within initial ports. The successful completion of these studies paves the way for bunkering trials, which are conducted to validate port safety frameworks and bunkering procedures. If successful, relevant ports may then allow the fuel to be bunkered on a case-by-case basis. Because the number of bunkering operations will initially be limited, an interim bunkering solution is likely to be used, for example, truck-to-ship bunkering, shore-to-ship bunkering, or chartered barge/gas carrier. Once demand grows and sufficient experience has been gained, ports will establish a licensing framework for bunker suppliers wishing to supply the fuel, kickstarting large-scale commercial bunkering and a move to a long-term solution, typically ship-to-ship using dedicated bunker barges/vessels.

These developments tend to be driven by a small group of leading ports, either major bunkering hubs interested in future-proofing their hub status or smaller players who see opportunities to expand their market share by being early movers. While the bunkering of the first wave of vessels may be concentrated at these leading ports, to reach maturity, bunkering must expand to cater to many more routes globally.

Fuel development and enablers

These developments must be supported by various enablers.

4 *Getting to Zero Coalition (2020),* "The First Wave: A blueprint for commercial-scale zero-emission shipping pilots", *Lloyd's Register Maritime Decarbonisation Hub (2021),* "First movers in shipping's decarbonisation - a framework for getting started"

This, importantly, includes fuel supply. While demonstrator ships may use a fossil fuel-based version of the molecule, by the time of the first generation of ships, they should move towards a lower-carbon version, and a zero/near-zero version by the time of the second generation of ships. This is necessary to validate the long-term supply chain for the fuel.

In terms of wider enablers, examples from other sectors show that national and regional government funding plays a key role in the research, development, and demonstration (RD&D) required in the proof of concept stage, alongside industry partnerships and collaborations. After this point, fuel certification, green premia or public funding covering the increased costs of operating on the new solution, and demand aggregation are required to provide assurances about the emissions reductions, cover the high cost of operating the new solution and enable a move to long-run bunkering solutions, respectively. Finally, getting to maturity requires a long-run business case to be in place, in addition to binding technical, liability, and other regulatory frameworks.

As such, the maturation process is a mix of innovation activities and supporting actions, which are not RD&D as such, but are vital enablers of progress.

Methodology and scope

This report zooms in on a set of progress areas and collates the learnings generated by early mover companies and organisations.

A survey of Getting to Zero Coalition members revealed high interest in early movers' experiences with ammonia, likely reflecting its lower maturity level compared to alternatives. Safety, emissions, bunkering, and engine developments were all within the top five areas of most interest. The same areas were popular for methanol, with some interest in operational and reliability-related learnings also.

Figure 3: Interest in different methanol and ammonia learnings among surveyed Getting to Zero Coalition members

Source: Survey of Getting to Zero Coalition members (N = 40)

Insights related to these areas were gathered from interviews with around 40 actors across the value chain who have either made investments in methanol or ammonia assets or are undertaking relevant research and demonstration projects in the two fuels. These included eighteen shipowners and operators, seven leading ports, three of the sector's main engine developers, as well as fuel project developers, researchers, trade associations, and shipping decarbonisation hubs. Interviews were conducted between March and May 2025 and data regarding vessel, bunkering, and fuel demonstrations and deployment was accessed in July 2025. As such, the report provides a snapshot of progress in mid-2025. It should be noted that progress is continuously being made on the fuels and developments after mid-2025 could change some of the report conclusions.

Like previous editions, the report focuses on technology availability, safety, and performance. Unlike previous editions, however, it emphasises ships and bunkering with only limited discussion regarding the status of fuel supply, which is both well-addressed by other publications and benefits from a specialist view, taking into account wider developments in the energy transition.[5]

5 *More information about the status of green methanol and ammonia supply can be found in the update reports and project databases provided by the* Ammonia Energy Association *and* GENA Solutions and the Methanol Institute.

Methanol

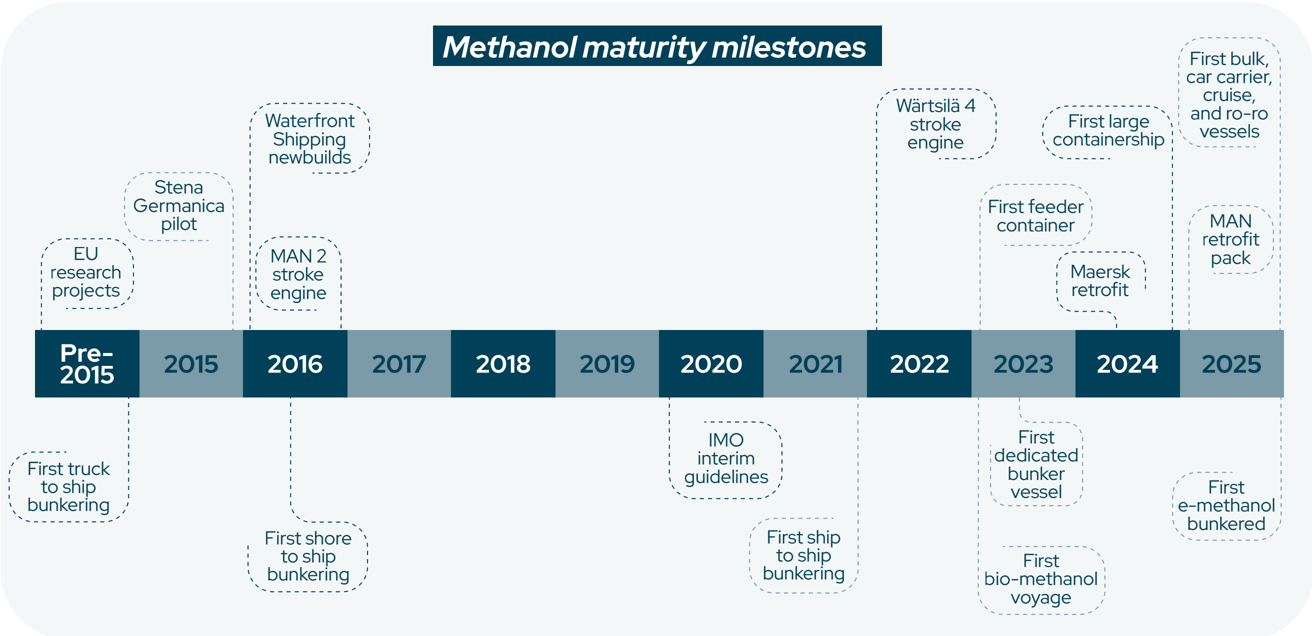
Current maturity

The use of methanol as a shipping fuel goes back a decade.

The initial impetus for its adoption in shipping came not from decarbonisation, but air pollution. In anticipation of the introduction of the Sulphur Emission Control Area in the Baltic Sea in 2015, several actors in Europe began to explore methanol as a means of reducing sulphur oxide emissions. A series of European Union (EU)-funded research projects, such as the Effship, SPIRETH, and MethaShip projects, eventually led to a real-world methanol pilot being undertaken by Stena Line's Stena Germanica in 2015 and the release of the first commercial methanol engine by Everllence the following year. These developments marked methanol's move past Proof of Concept and paved the way for the fuel's commercial uptake.

This came first on methanol carriers—specifically, a fleet of vessels owned by Waterfront Shipping, which hit the water in 2016 and represented the first newbuild methanol-capable ships.

Figure 4: Key milestones to-date in the development of methanol as shipping fuel

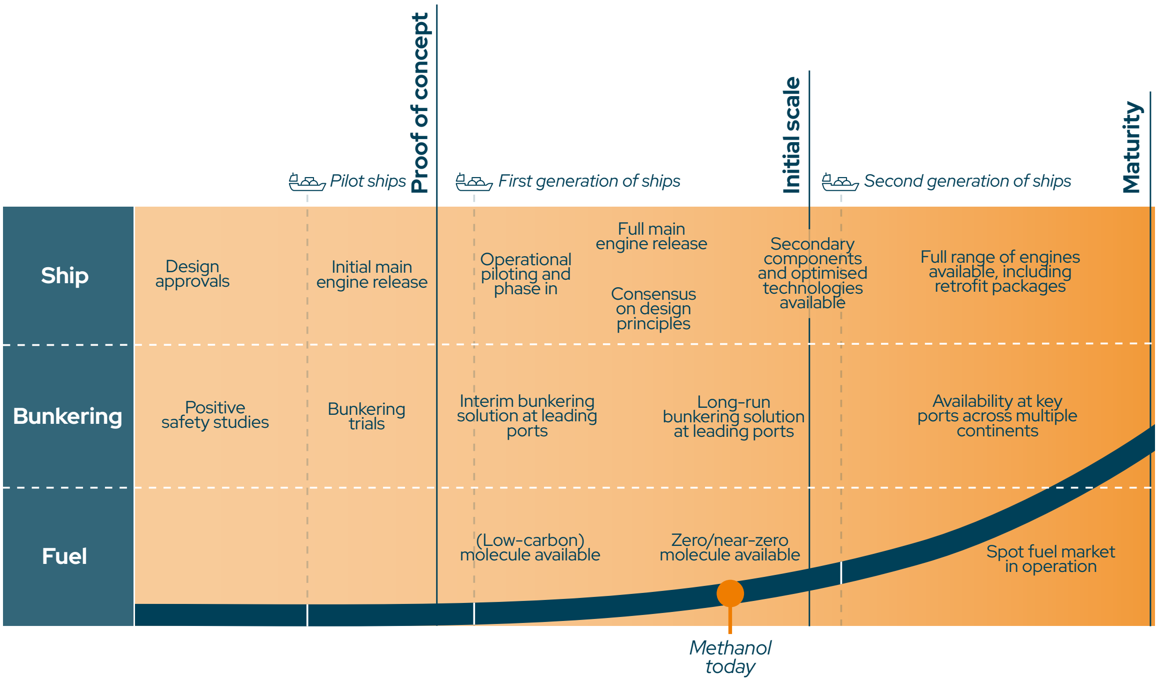


Sources: Global Maritime Forum compilation, based on Methanol Institute, EMSA, Clarkson's World Fleet Register, and corporate announcements

Wider interest in methanol increased after 2021, when Mærsk announced orders for a series of methanol-capable container ships, as part of the company's efforts to hit its 2030 greenhouse gas reduction targets. Since then, the number of ship orders and range of segments adopting the fuel have grown rapidly, while green methanol supply has begun to emerge to fuel them.

At the time of writing, around 60 methanol-capable vessels are on the water, more than 300 more are on order, and just under 20 ports offer methanol bunkering.[6] This has brought the fuel close to achieving initial scale.

Figure 5: Estimated maturity of methanol as a shipping fuel in mid-2025



Source: Global Maritime Forum assessment, based on stakeholder insights and Clarkson's World Fuel Register data

For this reason, there are a relatively limited number of RD&D projects focused on methanol, a fact reflected in last year's Pilot Mapping report. On the other hand, learnings about real-world use of methanol as a shipping fuel are becoming available.

Emerging learnings

The experience of early movers suggests that methanol is proving relatively simple to adopt. All shipowners, operators, and ports interviewed characterise the fuel in this way, describing it as "a very straightforward answer to our needs", "practical and pragmatic", and a solution "that works and can be scaled up". Initial learnings across three areas—ship design and technology, crew, and operation—support this.

6 *Data from Clarksons World Fleet Register, accessed 16/07/25*

Ship design and technology

Key findings	
Learnings	• Engine and fuel supply systems suitable for most ships available • Fuel and bunkering systems generally working well, but with teething problems around engines, including issues with fuel switching and high maintenance requirements, that are expected to be resolved shortly • Relatively minor design changes required for safety management, e.g., location of accommodation, and design of venting and firefighting systems • The fuel's lower energy density is not a showstopper, but creates a trade-off (methanol-powered ships bunker roughly twice as frequently as those burning conventional fuel) • Synergies available on some ship types, e.g., RoPax and car carriers • Retrofits are a significant undertaking, but feasible and more economical than retrofits to other main alternative fuels • Retrofitting requires minor changes to tanks and engines, but possibly extending the vessel
Gaps and barriers	• Ship design process time and resource-intensive

Newbuild ship design

A key emphasis in the design of methanol-capable vessels is safety. In general, early movers report that the safety profile of the fuel has been "much as expected" and comparatively "simple". This includes it being toxic at high concentrations, highly flammable, and burning with an invisible flame.

They cite two main sets of changes required for safety management— to venting systems, where it is important that no methanol is left in the fuel system after switching fuel modes, and around firefighting, given a fire may be hard to detect due to the invisible nature of methanol flames.

One company interviewed, X-Press Feeders, noted that while effective solutions are available for both challenges, understanding how to best implement these solutions was a time-consuming process. For example, the company had to redesign the ships' venting system, since this had previously been forward of the accommodation, which would create a risk that vented methanol would blow backwards towards the crew. Resolving this challenge took several months. In addition, major changes had to be made to the firefighting systems, involving new equipment, and a concerted effort to raise awareness and ensure the crews' readiness.

X-Press Feeders: Adopting methanol-powered feeder ships

Headquartered in Singapore, X-Press Feeders was the first company outside the methanol carrier segment to invest in methanol-capable ships, having ordered 14 methanol-capable feeder vessels since 2021.

The first eight of these are now in operation, with the remainder expected to be delivered by 2026. Of these, six have been deployed in the Baltic Sea, where they are running on bio-methanol, in what X-Press Feeders describes as "the first feeder network powered by green methanol in Europe". The bio-methanol is produced by OCI Global in a facility in the US and certified by the EU's International Sustainability and Carbon Certification (ISCC) as achieving a greenhouse gas reduction of up to 65%, based on the mass balance principle.

X-Press Feeders considered various options for fuelling these vessels, from methanol to ammonia and liquified natural gas (LNG). The company noted that ammonia was in the "very early stages of development" in 2021, with engines "still on the drawing board" and anticipated to be more suitable for deep sea operations than the short sea operations associated with feeder ships. Methanol compared favourably to LNG in two regards. First, less cargo capacity needed to be given up on the ship, at around 10% for methanol compared to almost 25% for LNG. Second, methanol presented lower CAPEX, with a premium of around 20 and 25% compared to a conventional ship for methanol and almost 40% for LNG. This CAPEX difference was especially pronounced for feeder ships, since CAPEX is a bigger component of the total cost of operating smaller ships.

While the company anticipated growing demand from customers for green methanol solutions, market uptake has been slower than expected. High costs of operating smaller ships have proven to be a barrier despite the vessels achieving 35% increases in fuel efficiency.

Company representatives said that the main alternative—the pooling mechanism under the FuelEU Maritime regulation—has not resolved the cost challenge since the value of overcompliance is being currently set by LNG ships, limiting operators' ability to monetise overcompliance from more-expensive methanol fuel. X-Press Feeders urges strong regulations to resolve this challenge, stating that "there is a cost difference between these fuels. Our experience has shown that once this fuel cost is reduced in some way everything else is manageable."

Another major consideration is methanol's lower energy density than conventional fuel.[7]

This has not been a showstopper for uptake, with interviewees reporting that methanol-powered vessels are "perfectly" able to complete the required voyages. This includes key deep-sea trades between, e.g., China and the US, Brazil and China, Australia and Europe, and North America and Europe. Indeed, methanol's energy density is highlighted as an advantage over ammonia, which has a lower energy density still. Wallenius Wilhelmsen noted that car carriers operate on long global routes—for example, departing from Europe and travelling to South Africa, Australia, and then to Northeast Asia. Its upcoming methanol-capable pure car and truck carriers (PCTCs) will be able to complete these routes with two bunkerings, one at each end of the route. In contrast, the company anticipates that an ammonia-powered PCTC would also need to bunker mid-voyage, in South Africa and Australia.

Exactly how far a given methanol-powered ship can travel before bunkering is, however, a trade-off that must be decided in the design process. Companies can either choose to minimise tank space to maximise cargo space and bunker more frequently, or maximise tank space and bunker less frequently by sacrificing some cargo space. Most interviewees have opted for the former, giving the ships an endurance roughly half that of equivalent conventionally-fuelled ships. Some, however, have opted for bigger tanks. This is based on engagement with prospective charterers, for whom ships having a similar endurance on methanol is important. These trade-offs are likely to be a standard element of the design process for methanol-capable ships. As Hapag Lloyd described it, "you can define it for yourself and have a design ready; define a number of tanks, which are able to sail a defined number of miles with one stop, and carry a given amount of cargo."

Beyond this trade-off, interviewees highlight benefits and synergies from adopting methanol, at least in certain shipping segments. Wallenius Wilhelmsen noted that, for stability, fuel tanks on a PCTC must be on the lower decks. While this might be expected to be a disadvantage, the "relatively small and simple" methanol fuel

7 Methanol has a lower heating value of 19.9 MJ/kg and volumetric density of 15.8 GJ/m3, compared to MGO's 42.7 MJ/kg and 36.6 GJ/m3.

tanks can be "hidden". This has limited the amount of lucrative high and heavy cargo space Wallenius Wilhelmsen has lost, but also "by distributing the fuel tanks, we have managed to improve the trim of the vessel, which reduces the ballast needs and ... has improved the fuel consumption". Stena Teknik reflect similar advantages on roll-on/roll-off passenger (RoPax) vessels. When designing the Germanica, a company representative noted that "the beauty of a RoPax [is that] you have that space available, so we could just simply transform some of the double bottoms into methanol tanks."

Technology

Technology has not been a limitation on shipowners ordering methanol-capable vessels. Since 2016, there has been an increase in the number and range of engines available. For example, Everllence (previously MAN Energy Solutions) now offers 45, 50, 60, 70, 80, and 95 cm bore engines, suitable for almost all medium and large ships, including the bulk carriers, tankers, and containerships that make up the vast majority of international shipping's emissions. The other major engine developers also offer products for the two and four-stroke markets, including WinGD, which now offers two-stroke methanol engines, and Wärtsilä and HiMSEN, which offer four-stroke methanol engines.

Despite this, X-Press reported experiencing some technology-related challenges. In the first instance, methanol-capable auxiliary engines for small ships are among those not yet commercially available. But the bigger challenge has related to spare parts, which are both "expensive" and face "lead times that are too long". This problem is not unique to methanol but has come to pose a problem for early movers, as they seek to operate the ships on a commercial basis.

In a similar vein, Mærsk indicated that, while the fuel and bunkering systems on its ships work well, the company has faced teething problems. Specifically, the material selection and short load reliability of some engine parts have meant that its methanol-capable ships need "too much maintenance". Everllence, the engine developer, is aware of these issues and has either solved or is working to solve them. In parallel, Mærsk intends to get "more running hours" on methanol, to help iron out the teething problems.

Figure 6: Teething problems encountered in methanol engine rollout and associated solutions

System element	Teething problem	Implemented solutions
1. High pressure hydraulic pipes	• Trapped air in pipes causing high pressure peaks and fatigue	• New pipe design without "goose neck" • De-aeration point moved to highest position
2. Nozzles	• Methanol nozzles on majority of Everllence B&W ME-LGIM engines in service last around 4,000 running hours	• Introduction of tungsten nozzles • Heat shield to reduce temperature/stress (being tested)
3. Cut off shaft	• Tendency to stick inside the valve if engine running 3-4 days on fuel oil, preventing methanol change over	• Change of material to tool steel • Installation of dummy nozzles if running on fuel oil for more than two months
4. Nitrogen purging	• Methanol filling sequence insufficient during change over to methanol • Nitrogen from purging not completely removed	• Sequential filling of engine • Lowering of methanol filling pressure

Source: Everllence

Retrofits

Learnings are also beginning to emerge regarding methanol retrofits. While the number of ships so far retrofitted to operate on the fuel is limited, Everllence has sold just under 30 two-stroke methanol retrofit packs to date, and one conversion has now been successfully completed.

One interviewee summarised the general sentiment by saying that methanol retrofit projects represent "a very big task, but a doable one".

Hapag-Lloyd, which is retrofitting five of its container ships to methanol, highlights that changes are needed to the engine, particularly around the piston heads and injection valves. Beyond the engine, "you have to do a lot on the fuel system", albeit less than LNG. While an LNG retrofit requires replacing the ships' tanks, "[for methanol] you can use the exact same tanks that you've currently got in ... [with] minor changes". A major change being contemplated by the interviewees is elongating ships to offset the fuel's lower energy density. This has already been done by Mærsk, whose Mærsk Halifax was extended by 15 metres in length to add 690 twenty-foot equivalent units (TEU) of capacity to the ship. Hapag-Lloyd further notes that it is at present easier to retrofit large ships, since engines with bigger bore sizes have more space for the necessary modifications.

Overall, interviewees see three current challenges around methanol retrofits, all of which relate to commercial rather than technological factors.

First, there is a long timeline for retrofit projects, with estimates ranging between three months and a year. Even at the lower end of this range, this represents a major conversion according to IMO rules and thus requires new engine certification. Respondents stressed that this is a long time to have a ship out of service from a commercial point of view. However, it is expected that retrofits will speed up as the industry gains experience. As a Hapag-Lloyd representative put it, "we assume the first one [for methanol] will take a bit longer, but the last ones will go faster, and we will learn a lot on the way".

Second, while methanol retrofits are expected to be more economical than retrofits to other alternative fuels,[8] they nonetheless represent a "very expensive proposition". Hapag-Lloyd views this as an investment. "We agreed to start by testing the waters with some retrofits. While the upfront investment in retrofitting may seem slightly higher compared to integrating the solution into a newbuild, it's important to consider that a newbuild is significantly more expensive overall." The company pointed to the potential to spread costs (and learnings) from retrofits through partnerships, such as the one Hapag-Lloyd entered with Seaspan.

Finally, there are some concerns about the availability of suitable shipyards able to undertake these retrofits, with "not too many" being both interested and capable. This dynamic is expected to create first-mover advantages, both for owners who secure retrofit slots early and investors in relevant yards who get in before demand increases. Everllence noted that several of the major Chinese shipbuilding groups are already acting on this opportunity, with plans to scale up their capacity for retrofit projects.

8 *See Mærsk Mc-Kinney Moeller Center for Zero-Carbon Shipping,* "Vessel design considerations for methanol retrofits" *for further information on methanol retrofit costs*

Crew

Key findings	
Learnings	• Crew training required, but not especially complex or long • Positive perceptions of the fuel among seafarers • Bottleneck encountered in the availability of training, but ecosystem of training providers now in place
Gaps and barriers	• N/A

Interviewees recognised that crews need training to be able to safely and effectively operate methanol ships.

Such training is not expected to be especially complex or time-consuming, with one respondent estimating that a methanol training course would take around ten days for its seafarers to complete.

However, there have been bottlenecks in the availability of methanol training for first movers. X-Press Feeders said that the training process for crews on its methanol-powered feeder ships took nearly two years and was “really, really difficult”.

One of the key challenges was the limited availability of training for dry cargo crew. Unlike seafarers from the methanol carrier segment, dry cargo crew have to start from scratch, beginning with the basic certifications required for methanol operations. The higher training needs of dry cargo crews were echoed by Diana Shipping, which has ordered two methanol-capable Kamsarmax bulk carriers, and stated that “today, the average crew or officer in the bulk segment is not ready for [zero-emission shipping] operations”. In this regard, some interviewees propose that methanol, being relatively easy to handle, could act as a stepping stone for the uptake of other fuels later. To facilitate the learning process, Diana Shipping plans on using a combination of crew members from its existing pool and crew members from methanol carriers aboard their forthcoming ships.

X-Press Feeders also cited limited facilities and instructors as a hurdle. However, companies with methanol-capable ships currently in the orderbook suggest that this situation has now changed, with a wider training ecosystem coming into place. Diana Shipping noted that there are several options available in terms of advisory companies and training providers for crews on their upcoming vessels, including but not limited to the engine developers.

Meanwhile, the Maritime and Port Authority in Singapore has also established a Maritime Energy Training Facility to support the training of international seafarers for zero- or near-zero emission fuels. The facility has so far provided methanol training to more than 620 seafarers.

Operation

Key findings	
Learnings	• Methanol bunkering operations are similar to fuel oil, with the smallest risk contours of the main alternative fuels and proven SIMOPs • Ability to use conventional bunker barges with limited modifications, but dedicated methanol bunker vessels are also emerging • Positive perceptions of the fuel among port and community stakeholders • Mostly grey methanol bunkered to-date • Sufficient green methanol supply is available, with China leading developments
Gaps and barriers	• Offtake agreements needed to access supply; this remains problematic due to premium, long-term fixed price nature of the commitment, certification challenges, and rising geopolitical risks • Bio-methanol currently offers a 65-70% emissions reduction, below its potential emissions reductions • Challenging business case for dedicated methanol bunker vessels, including retrofitted conventional vessels

With methanol ships operating commercially, a key element is the availability of bunkers.

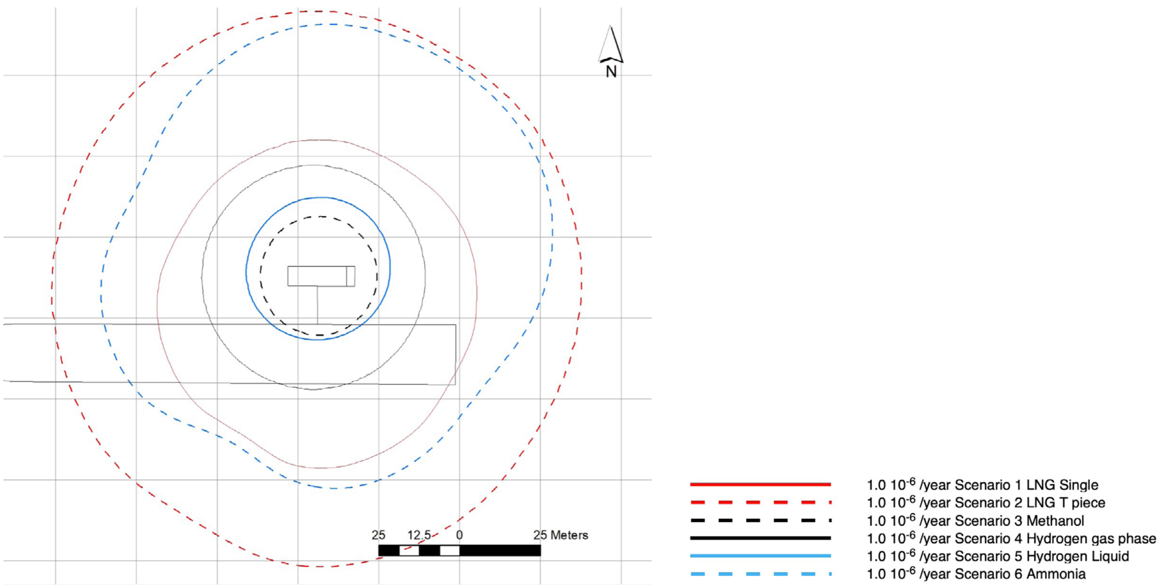
While parameters and requirements for truck-to-ship and shore-to-ship bunkering have been well-understood for several years, the key developments have been the validation of ship-to-ship and simultaneous operations (SIMOPs) – the way most larger ships are bunkered today and standard operating practice for container ships and car carriers, respectively. Ship-to-ship methanol bunkering was first demonstrated in 2021 and has been scaling up since; among interviewees, Mærsk has successfully completed around 30 methanol bunkering operations in multiple ports, while X-Press Feeders has been regularly bunkering the fuel in Rotterdam for more than a year. Many operations have been on a SIMOPs basis.

Those with experience describe methanol bunkering as "fairly straightforward" from an operational standpoint and emphasise the similarities between bunkering methanol and fuel oil.

Port of Antwerp-Bruges stated that while significant preparations were required for methanol bunker operations at the port (described below), "in terms of the operations themselves, there are no large differences" between the two fuels, which are both liquid at ambient temperature and pressure. "We didn't really experience any more restrictions," a port representative said, adding that the main difference was "the fact that the terminal operators need to be aware that methanol is bunkered at their berths, hence they are an essential part of the joint plan of bunkering operations; for fuel oils they are not, but with methanol they have to be involved." This also required the port to provide training that it "[doesn't] necessarily do with a regular bunkering procedure". Regarding SIMOPs, the port said that "certain considerations had to be addressed", but the core planning needed was confined to "deciding the circumstances under which the bunkering could be started and taking safety distances into consideration when sequencing container movements".

Similarly, the Port of Amsterdam reflected that methanol is "the easiest [to bunker] out of the alternative fuels". While "you still have to do a lot, with good technology and procedures, it's very feasible to perform". The port highlighted a safety study that showed that while the risk contours for methanol bunkering are bigger than fuel oil, they are smaller than those for both ammonia and LNG, and less affected by weather conditions.

Figure 7: Example risk contours calculated for truck-to-ship bunkering of alternative fuels at the Port of Amsterdam



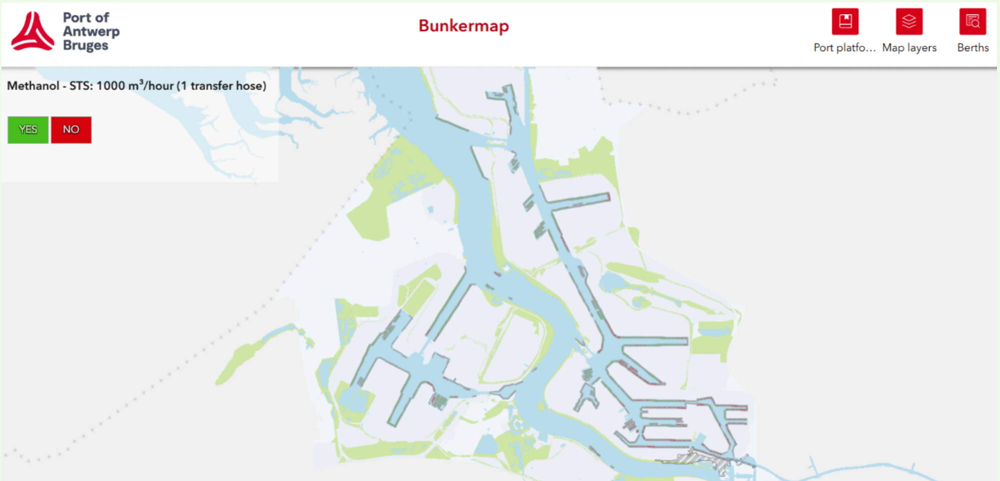
Source: Aviv for Port of Amsterdam, Risk analysis - Bunkering of alternative fuels in the port of Amsterdam

Technical managers echoed this perspective. Hong Kong-based Wah Kwong manages both LNG and methanol bunker vessels at the Port of Shanghai, where it executed the bunkering of Astrid Mærsk with 500 tonnes of green methanol in April 2024.

Wah Kwong said that it was less complicated than LNG bunkering operations, which require lengthy preparations before and close management of pressure and temperature during the operation. For methanol, the task was mostly about "ensuring smooth ship-to-ship discharging and having good coordination with the receiving ship." The involved crew received around two weeks of training, covering classroom explanations of the port regulations and site visits to the shipyard to familiarise themselves with the ship before undertaking the operation.

Port of Antwerp-Bruges: Scaling up methanol bunkering

Fig. 8: Bunker map showing where ship-to-ship bunkering of methanol at 1,000 cubic metres per hour is permitted at Port of Antwerp



Source: Bunkermap Port of Antwerp-Bruges

Port of Antwerp-Bruges is one of the world's largest bunkering hubs and has the ambition to become a multi-fuel port.

The port bunkered around 11,000 tonnes of green methanol in 2024, the most of any port globally. While this may be a small volume compared to the roughly eight million tonnes of fuel bunkered at the port yearly, 11,000 tonnes would represent a significant proportion of many proposed green methanol plants, meaning that just a few bunkering operations a year can be sufficient to kickstart a green methanol production project.

The port's first methanol bunkering operation was a SIMOPs bunkering of the Ane Mærsk in April 2024. To prepare for the operation, the port undertook a thorough risk analysis starting late 2023. This explored possible risks associated with methanol bunker and the impact it could have on infrastructure and public safety. It resulted in an online bunker map that shows where and how methanol can be bunkered in the port.

The bunkering operation was planned and performed based on these findings. Extra safety precautions were taken to ensure it took place without incident. For example, while subsequent methanol bunker operations have taken place at night, the start of first methanol bunkering operation was done during daylight hours to enhance visibility.

In terms of infrastructure, the methanol was delivered by an existing chemical barge. The port noted that existing chemical barges are sufficient to meet initial demand for methanol bunkering. They will, however, benefit from dedicated methanol bunker barges, of which several have been ordered for use in the ARA region. These are specifically designed and equipped with the necessary infrastructure to enable efficient bunkering operations at greater scale.

Since the Ane Mærsk bunkering, the port has approved methanol bunkering operations on a case-by-case basis. It is now in the process of drafting regulations to incorporate methanol into its licensing system, paving the way for full scale methanol bunkering by 2026.

Ports and operators report relatively few challenges around infrastructure despite the limited market for methanol bunkers at this stage. Interviewees highlighted existing bunker barges/chemical tankers and the ability to use existing methanol storage tanks as key advantages. This has facilitated the establishment of so-called "interim bunkering solutions" at leading ports, enabling methanol bunkering to be performed on a case-by-case basis.

While such interim solutions have proven to be safe and effective in servicing the early wave of methanol-capable ships, the Port of Rotterdam emphasised that large-scale methanol bunkering requires investment in dedicated methanol bunker barges. "This just makes it more efficient [and ...] a much quicker operation to get methanol bunkers," a port spokesperson said. This is underway, with, for example, Rotterdam now having two dedicated methanol bunkering barges and Shanghai having one. These investments have been based more on a desire by the bunker suppliers to be first movers in the transition than strong business case fundamentals, with Wah Kwong stating that the methanol bunker vessel in Port of Shanghai saw relatively little use in 2024 and has relied on the ability of the port, as a state-owned enterprise, to make investments in service of longer-term goals—in the case of Port of Shanghai, becoming a major green bunkering hub.

Finally, engagement undertaken by early movers suggests that methanol enjoys positive perceptions among port workers, terminals, and wider port stakeholders. As a testament to this, one port recounted that one of its terminals, which has been opposed to LNG bunkering, allowed methanol bunkering operations. Based on the success of these methanol bunkering operations, the terminal has changed its position on LNG bunkering and will now allow this in the future too. At the same time, ports stressed that proactive outreach to local communities and other stakeholders remains important for the implementation of methanol bunkering. This has, for example, taken the form of handing out information leaflets informing port workers that bunkering of methanol is going on, explaining what methanol is and the nature of the risks posed when undertaking the bunkering operations.

The supply opportunity/challenge

Against this background, interviewees agreed that the main hurdle to scaling up the fuel further is the availability of green methanol molecules. Indeed, most methanol used onboard ships to date has been grey methanol,[9] with only small volumes of bio-methanol being bunkered since 2023 and the first volumes of e-methanol being bunkered by Mærsk in Denmark in May 2025.

This is not because of a lack of potential supply. In fact, announced green methanol projects—which include both bio and e-methanol projects—could supply around 40 million tons of the fuel. A notable development in this regard is China's emergence as a leading production location, accounting for more than half of the potential supply. All operators interviewed highlighted China's advantages in cost, speed of the delivery, and contracting terms, noting that Chinese-produced fuel is generally several hundreds of dollars per tonne cheaper than that produced in Europe or the Americas, can be made available a year or more quicker than in other regions, and can be procured on medium rather than long-term contracts. These advantages mean that China is expected to play a key role in scaling green methanol production and availability.

The key bottleneck is the advanced purchase commitments (so-called "offtake agreements") that project developers require to move to construction. Just four million tonnes worth of green methanol projects have progressed past final investment decision to date, significantly below the volumes needed to power the methanol-capable vessels set to be delivered in the coming years.[10] This is not a new challenge, with the multiple obstacles stopping shipping companies signing offtake agreements well understood.[11] Current geopolitical tensions, as well as greenwashing and certification concerns, have however emerged as additional challenges, with one shipping company stating that it has not purchased Chinese green methanol because of these risks.

Meanwhile, interviewees note that the bio-methanol currently being used and/or offtaken to date offers 65-70% emissions reductions. This is significantly below the 90%+ emissions reduction possible, meaning that the fuel is yet to hit its full emissions reduction potential. This is attributed to the transport of the molecule, which can generate significant emissions, especially over the long distances involved in moving it from, for example, Northern China to a port such as Shanghai. E-methanol can achieve well-to-wake emissions reductions in the range of 90-95%.

9 Ca 94,000 tonnes globally in 2023, per the most recent available data

10 See, for example, a BNEF and Climate Technology Coalition White Paper on "Scaling up Hydrogen"

11 As of June 2025, GENA Solutions estimates that methanol dual-fuel vessels on the water and on order could consume up to 14.5 Mt of methanol by 2030, assuming a fuel mix of 95% methanol and 5% pilot fuel. However, they expect actual consumption to range between six and 11 metric tonnes in 2030.

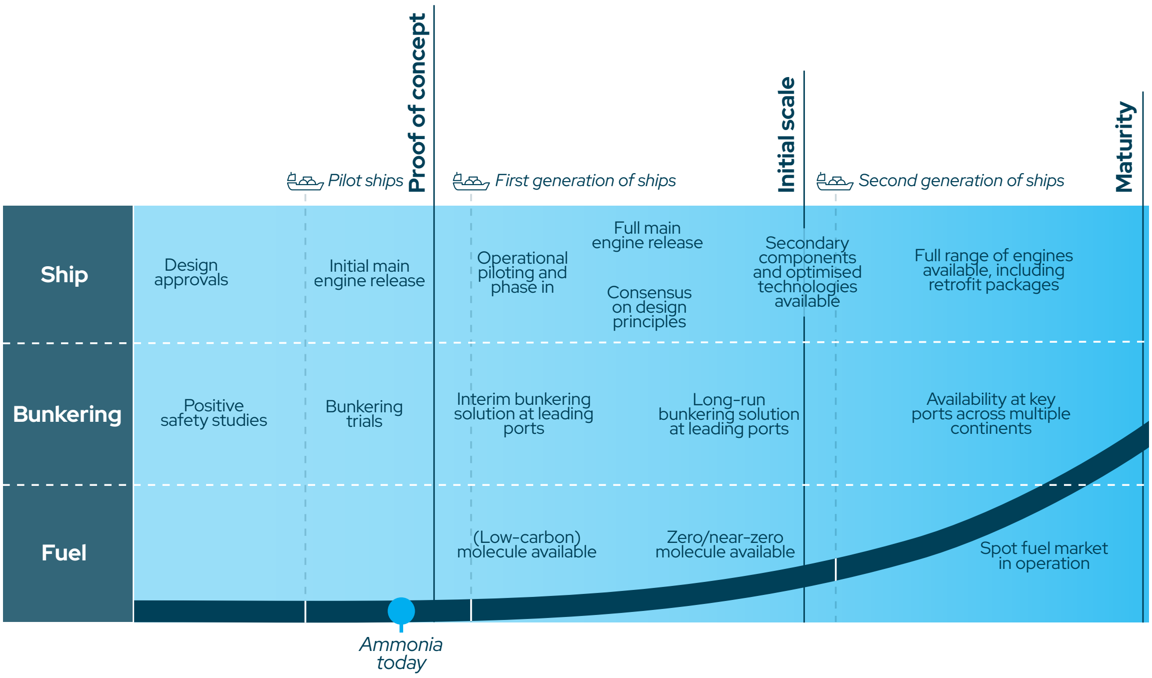
Ammonia

Current maturity

The exploration of ammonia as a shipping fuel started later than methanol. Getting to Zero Coalition project data shows that interest took off around 2019, shortly after the implementation of the IMO's initial greenhouse gas strategy. In addition, ammonia has challenging chemical properties, most notably being less flammable and significantly more toxic than alternatives. As such, the fuel remains at an earlier stage in its scale-up than methanol.

However, it is making rapid progress thanks to a high level of interest within the industry.

Figure 9: Estimated maturity of ammonia as a shipping fuel in mid-2025



Source: Global Maritime Forum assessment, based on stakeholder insights and Clarkson's World Fuel Register data

Smaller experimental vessels have now been piloted[12] and the first generation of commercial newbuilds capable of operating on ammonia are set to hit the water from early 2026 on. At the time of writing, they comprise over 40 ships, of which a majority are liquefied petroleum gas (LPG)/ammonia carriers and large bulk carriers.[13] This has been facilitated by strides in engine development. A four-stroke

12 They include the Fortescue Green Pioneer, Hefei Comprehensive National Science Center Institute of Energy and Shenzhen Haixu New Energy Anhui, COSCO Yuantuo 1, NYK Sakigake, and Amogy Kraken. An ammonia fuel cell has also been installed and used to produce auxiliary power onboard the supply vessel BERTHA B.

13 Data from Clarksons World Fleet Register, accessed 16/07/25. While LPG/ammonia carriers and bulk carriers represent the majority of ammonia-capable ships ordered, other types of vessels have also been ordered, including one containership - the Yara Eyde.

ammonia engine has been available from Wärtsilä since 2023 and two-stroke engine tests are nearing completion, with WinGD installing its first engine in July 2025.

Orders have been placed for more than 60 engines overall. Bunkering trials are also now underway at a handful of leading ports, with 12 having been successfully completed to date.[14]

These developments position ammonia just before the proof of concept stage, meaning the feasibility of using the fuel is close to being proved.

Emerging learnings

Three learning areas stand out as particularly important and have been key focuses within the industry: safety, emissions, and bunkering. Though more remains to be learnt, knowledge gaps in these three areas are beginning to narrow.

Safety

Key findings	
Learnings	• Significant design changes needed: › Segregating sections for leak safety and no venting under any circumstances emerging as guiding design principles › Package of safety measures and technologies required e.g. double-wall piping, additional gas detectors, remote stop, automation, increased ventilation, refrigeration, and water sprays/curtains • Challenge around safely and efficiently managing boil-off gas due to lack of suitable auxiliary engines • Mixed but manageable response from seafarers to working on first ammonia ships • Life on board expected to be broadly similar, although more complex • Hands-on experience and learnings from ammonia carriers being incorporated into training
Gaps and barriers	• Lack of understanding around ammonia spills at sea

Interviewees reflect that "a lot of changes are required" to design safe and efficient ammonia-capable vessels.

Resources company BHP is working towards the development of ammonia-capable bulk carriers, with a view to deploying ammonia dual-fuelled bulk carriers before

14 *Trials have taken place at the ports of Dampier, Dalian, Ngqura, Rotterdam, Singapore, and Yokohama, near Ceuta in Spain, on Chaohu Lake in China, and on the Hudson River in the US*

2030. The starting point for this work has been the IMO interim guidelines, which BHP is assessing to consider how they can best be implemented in practice. For example, a requirement in the interim guidelines for a safe haven where crew can shelter in the event of a fuel leak has led to some "very material changes to the vessel design and space allocation".

In general, BHP emphasised two guiding principles that it is working with vessel owners to apply in the design of the ships:

- **Segregate sections for leak safety:** "Everything needs to be redesigned based on the principle that if and when there is a leak, you should be able to close the area off," a BHP representative stated. Crucially, this includes "a complete disconnection from the accommodation block" to ensure the safety of the crew. This is a departure from business as usual, as the accommodation block, engine room, and cargo zones in conventional vessels are usually interconnected to enable efficient operations. Segregating sections, therefore, comes at some expense to operational efficiency.
- **No release of ammonia under any circumstances:** Because of ammonia's toxicity, it is critical that the fuel is not released into the environment, given the catastrophic impact this could potentially have on the crew, marine environment, and/or ports. One challenge in this regard is managing boil-off gas. BHP noted that "in LNG vessels, boil-off gas is consumed in the auxiliary engines. However, there is currently no known auxiliary engine that can use ammonia as a fuel. Until that development happens, ship designers need to think about [how to handle the] ammonia boil off safely". BHP said that multiple approaches could be considered, including a reliquefication system that reuses the ammonia boil-off or the inclusion of an ammonia gas recovery and treatment system. Either or both of these would, however, involve a trade-off between capital expenditures and operating expenses, which requires a prioritisation exercise.

Other interviewees echoed these principles, suggesting that, even at this early stage, convergence is happening around the principles that should be applied to design safe ammonia-powered ships.

In terms of specific safety measures and technologies, CMB.TECH noted that a "pretty standard toolkit" is available, which "shipping has already had for years". 'Tools' frequently mentioned by interviewees include double-wall piping, additional gas detectors, remote stop, automation, increased ventilation, refrigeration, and water sprays/curtains. These correspond closely to the measures recommended by classification societies and research organisations.[15]

15 *See, for example,* Emerging ship design principles for ammonia-fueled vessels

CMB.TECH: Designing safe ammonia-powered vessels

Belgian shipowner CMB.TECH has ordered a series of ammonia-capable Newcastlemax bulk carriers. The vessels are currently under construction and are set to be delivered starting in early 2026, making them among the first ammonia-capable ships to hit the water.

The design of the ships was based on an alternative approach using risk assessments to prove the ships meet safety levels equivalent to conventional vessels. Anglo-Eastern, with whom CMB.TECH partnered on the design, noted that experts from the gas segment were included in the design process to ensure existing learnings where leveraged.

The resulting design features two 3,000m³ tanks on deck, which can store around 4,000 tonnes of ammonia in total. This gives the ships an endurance of 11,000 nautical miles, allowing them to do two roundtrips between Australia to China before needing to bunker. The positioning of the tanks on the deck means that the ships do not lose cargo space.

Source: CMB.TECH and Anglo-Eastern

The ships feature an extensive set of safety measures:

- Each ship has almost 60 ammonia detectors alongside 11 remote stops situated in different locations across the ships, enabling an instant switch to diesel if needed.
- The ammonia is kept refrigerated, with boil-off gas managed through a reliquefaction system, which sends it to the holding tanks. The system is designed with a holding capacity sufficient for a full trip to avoid any issues arising mid-trip.
- CMB.TECH and Anglo-Eastern also emphasise the importance of zero venting. To prevent venting in the case of a leak in the fuel processing room, the ventilation in the room will be shut off, and a water spray deployed, absorbing the ammonia and allowing for a transfer of the aqueous ammonia solution to a holding tank for safe disposal.

Crew

In parallel with ship design, training courses and facilities are being rolled out to ensure crews are ready to operate the first vessels. This includes Alam Maritime Academy in Malaysia and Anglo-Eastern Maritime Academy in India, both of which are now delivering ammonia training. Some 74 officers and 165 crew members had been through the basic ammonia course at Alam Maritime Academy as of March 2025. Upcoming courses at the Academy included handling, operations, safety, and emergency response. These were to be completed by the crews in "different bursts". Such courses last three weeks, making them "a couple of days" longer than equivalent LNG courses.

To facilitate hands-on experience, Anglo-Eastern has installed an ammonia bunkering skid for hands-on engine training. This is supported by simulator training based on the actual fuel systems of forthcoming ammonia-capable ships. Meanwhile, Alam Maritime Academy has simulators for operations and cargo handling, with an engine room simulator set to be installed. To further familiarise crews with the molecule, both plan on sending crew members to shipyards and/or placing them on ammonia carriers.

There has been a mixed response from crews to the idea of working on ammonia-powered vessels. While some seafarers have volunteered to be on the ships, seeing it as an exciting innovation and/or being attracted to the ship's green credentials, others are said to have had "lots of questions". Concerns are reported to have dissipated as crew members become more familiar with the fuel.[16]

Finally, indications are emerging about what life may be like on board. Overall, AET expects life on its ammonia-capable tankers to be broadly similar to that

16 See also the results from a recent survey of seafarers about their perceptions of ammonia conducted by the Mærsk Mc-Kinney Moller Center for Zero-Carbon Shipping on a conventional ship. Crew members will not need to wear additional personal protective equipment (PPE), except for those entering toxic spaces and first responders who participate in emergency response. The main difference is the complexity of operating the ships, which is expected to be higher. Höegh Autoliners, which has a series of ammonia-capable PCTCs under construction, point to procedures for entering restricted areas, special drills and procedures in case of leakages, and specific safety requirements for bunkering as the biggest areas of complexity. This aligns with findings from recent industry studies.[17]

Figure 10: Overview of PPE and safety gear used on the Fortescue Green Pioneer

Context	Required safety gear
Restricted zone	• Standard PPE • Gas hood • Portable gas detectors • Diphoterine aerosol can
High risk hazardous zone	• Chemical protection suit • Lined nitrile chemical gloves • Fire/HAZMAT rubber boots • Diphoterine aerosol can • Positive pressure mask and hood • GX-3R portable gas detectors
Emergency response	• HAZCHEM suit • Self-contained breathing apparatus set • Fire/HAZMAT rubber boots • Rescue/fire helmet • GX-3R Pro or GX-6000 calibrated gas detectors

Sources: Fortescue

Engine and emissions

17 *See, for example, the assessment in Maritime Just Transition Task Force (2024),* "Considerations of Training Aspects for Seafarers on Ships Powered by Ammonia, Methanol, and Hydrogen"

Key findings	
Learnings	• 90-95% tank-to-wake greenhouse gas emission reduction likely to be possible • Ammonia slip and nitrogen oxide emissions expected to be IMO compliant • Engine emissions highest for four-stroke engines and at lower engine loads • Two emissions abatement technologies required: ammonia release mitigation system and selective catalytic reducer • First ships not expected to achieve full emissions reduction potential immediately: › Fuel will initially be used 25-50% of the time to test systems › Conventional auxiliary engines are often retained; ammonia not used within ports or when manoeuvring • Blue ammonia (produced from natural gas with applied carbon capture and storage) likely to be used, particularly early in ammonia's introduction
Gaps and barriers	• Lack of some engine sizes, particularly suitable auxiliary engines and main engines for large container ships, as well as ammonia boilers • Real-world emissions profile remain uncertain; operational data from ammonia-powered ships required

A key attraction of ammonia as a shipping fuel is that it does not contain carbon and thus does not produce carbon emissions when burnt. If the fuel is produced with green energy sources, ammonia would thus significantly reduce a ship's carbon emissions.

However, as interest has grown, awareness has increased about the other emissions that could come from ammonia's use as a fuel. Specifically, four types of emissions present risks:

- **Ammonia slip** - highly toxic, presenting a safety risk to people and the environment
- **Nitrogen oxides (NOx)** - contributes to the formation of acid rain and smog
- **Nitrous oxide (N_2O)** - a greenhouse 273 times stronger than carbon dioxide

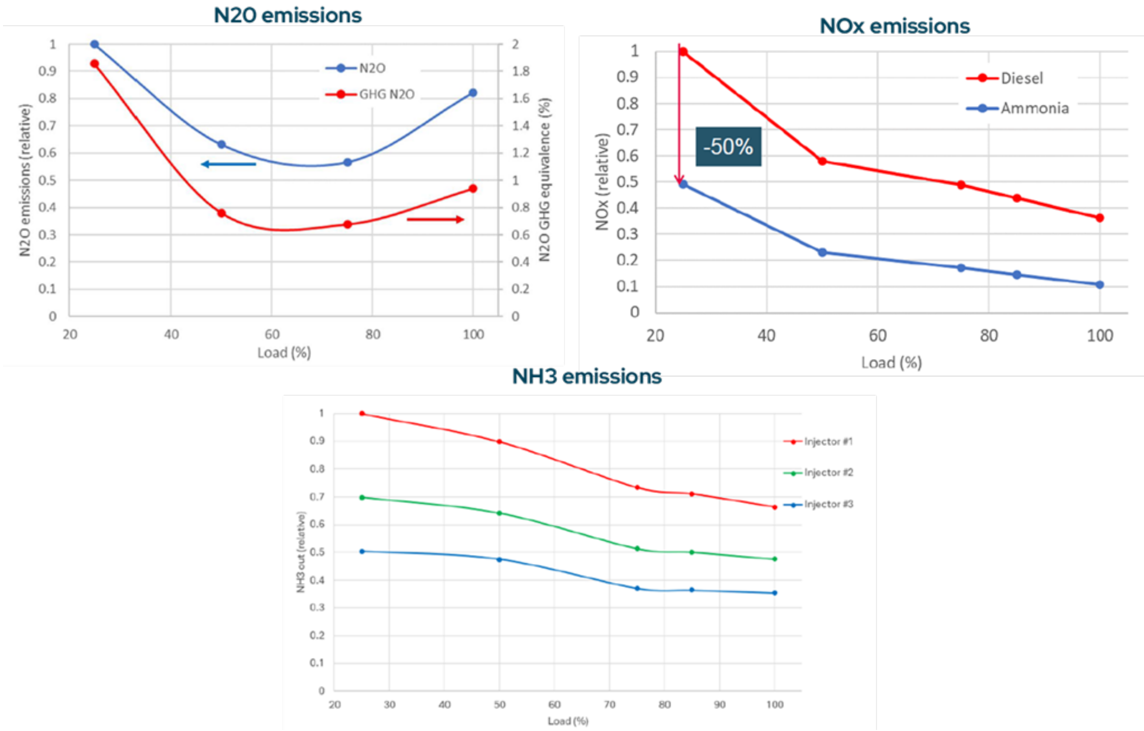
over a 100-year timeframe

- **Greenhouse gases from the pilot fuel** required for engine ignition

Recent research studies and NGO advocacy have suggested that these emissions, particularly N_2O emissions, could be a showstopper for ammonia if they are not adequately addressed.[18]

Since the engines have been under development, the scale of these emissions has remained uncertain. However, more clarity is beginning to emerge, as the engines have moved to advanced testing.[19,20]

Fig. 11: Test results for Everllence two-stroke ammonia engine



Source: Everllence

In terms of climate risk, results suggest that 90-95% reductions in tank-to-wake

18 See, for example, Using ammonia as a shipping fuel could disturb the nitrogen cycle | Nature Energy *and* TransparencyCall - Engine Makers - AMMONIA letter ACTIVE

19 *Engine manufacturers and research agencies, such as Oakridge National Lab—which has been testing ammonia engines—stressed the difficulties in extrapolating from smaller-scale research engines, since engine behaviour does not scale linearly and the research engines being used employ a different combustion approach than the commercial engines under development. Fortescue emphasised a similar point regarding its Green Pioneer. Due to the speed of the project, the ship uses a retrofitted engine. This created limitations, including using pre-mixed injection, resulting in the ship only achieving a 50% ammonia fraction. While this exceeded the initial target of burning 30% ammonia, it is significantly lower than what is possible. Indeed, Fortescue is confident that it will be able to achieve a 95% ammonia share on future newbuild ammonia-capable ships.*

20 *Readings from experimental vessels are consistent with these results, with inspections of NYK's Sakigake indicating no ammonia leakage after 300 hours of ammonia operations. Cf.* Emission performance of ammonia-fueled, four-stroke marine engines

emissions are plausible with the engines under development.[21] Everllence and Wärtsilä note that this supersedes their previous, publicly communicated targets of 90% and 70% reductions in tank-to-wake emissions respectively.

Everllence reports that N_2O emissions from its two-stroke engine are typically well below 5 ppm and WinGD reports N_2O emissions of below 3 ppm. This is equivalent to less than 1% of the emissions from a conventional engine. The level is, however, sensitive to engine load. Everllence tests show that emissions are indeed slightly higher at lower engine loads; while the carbon dioxide equivalent emissions from N_2O formation are around 1% of those produced by a conventional engine at 100% engine load, they have been found to be no more than 2% at low engine loads. Wärtsilä reports 10-15 ppm of N_2O emissions exiting their engine without aftertreatment. This is reduced by 75% with aftertreatment.

Meanwhile, Everllence hit its target of 5% of energy coming from the pilot fuel at 100% load. Tests show this increases to around 7% at low engine loads. Four-stroke engines, used on short-sea ships, typically require more pilot fuel than two-stroke engines, used on deep-sea ships. However, Wärtsilä reported that its four-stroke engine requires a roughly similar level of pilot fuel as Everllence's two-stroke engine.

At the same time, operators underscore that ammonia-powered vessels will not hit 90-95% emissions reductions overnight.

First, the introduction of the first vessels will not be a one-time event, but a gradual process. Specifically, they plan to run the first ships on ammonia between 25% to 50% of the time for up to a year, as "there just will be so many findings that we will need to work through and address". Only after this "hurdle of technical competence" is crossed will operators consider higher levels of ammonia use. Overall, they expect that "the learning curve will be steep [...] and the pace of change will be slow".

Second, suitable ammonia auxiliary engines and boilers are not yet available and are unlikely to feature on vessels before 2030.[22] Operators are also not expected to use ammonia when manoeuvring or at port, with question marks about when or whether this will happen (one interviewee notes that "manoeuvring is not going to happen on ammonia for a very long time"). Yet, it is noted that emissions from these operations typically form a small proportion of a ship's overall emissions footprint, estimated at around five percent by another interviewee.

Finally, blue ammonia is expected to play a role in fuelling these vessels, with first movers highlighting its lower cost and greater availability before 2030 compared to

21 *See recent articles by the Ammonia Energy Association* Emission performance of ammonia-fueled, two-stroke marine engines *and* Emission performance of ammonia-fueled, four-stroke marine engines *for complementary overviews of these results*

22 *Additionally, the roll out of main engines is focused on medium-sized vessels; 90-bore engines, as used on large containerships, are not expected to be released until "a couple of years" after the first engines.*

green ammonia.[23]

Beyond climate risks, the results show reduced NOx emissions exiting the engines compared with diesel, with Everllence's testing demonstrating a reduction of up to 50% and WinGD's "well below those generated during diesel use". The engines are thus expected to naturally comply with IMO Tier II NOx requirements but require a selective catalytic reducer (SCR) to meet the more stringent Tier III requirements. Wärtsilä's four-stroke engine is also expected to produce NOx levels "well below the Tier III level" with use of a SCR. SCR systems will be supplied with all three engines.

Finally, WinGD reports less than 10 ppm ammonia slip exiting its engine. This is achieved without an ammonia release mitigation system. This is below the threshold for ammonia leakage set by the IMO's interim guidelines for ammonia-fuelled vessels, which are 25 ppm in enclosed spaces and 110 ppm in secondary enclosures. Everllence has developed several possible approaches to managing ammonia slip and is awaiting final guidance from the IMO about the regulatory framework for ammonia slip before choosing which approach to implement. It does not expect an ammonia release mitigation system to be used in normal operations, only in the event of emergency ammonia purging. Both engine manufacturers intend to use any remaining ammonia slip as a reacting agent in the SCR, reducing the amount of urea that ammonia-powered ships will need to carry. Four-stroke ammonia engines currently show considerably higher levels of ammonia slip. These will need to be treated with an ammonia release mitigation system, which reduces emissions from Wärtsilä's four-stroke engine to below 30 ppm and close to 0 ppm in most cases.

Overall, while the engine manufacturers expect their results "will be duplicated within a certain amount of tolerance in the real world", they cannot guarantee this. This makes monitoring the first vessels important. In this regard, Everllence has partnered with "a few selected, really experienced, big owners" to pilot its engine. As part of these pilots, the engines will be live monitored to ensure they are performing as expected, with Everllence able to detect and address any faults with the engines before they pose a safety risk. They confirm that they will also collect "R&D data" from the pilots, which will be used to finalise the engine design ahead of a full sales release. Several interviewees suggest that there would be value in additional independent evaluations, particularly of these ships' N_2O emissions, given the major uncertainties small deviations in performance could have for the sector.

One remaining gap highlighted by several interviewees concerns ammonia spills, with very little information being available about the environmental and safety implications of an ammonia release at sea. Indeed, INERIS (the French National Institute for Industrial Environment and Risks) noted that existing data comes from laboratory tests, which are not necessarily representative of realistic shipping spills. This makes it difficult to model and understand the best way to mitigate the impacts of such a spill. To close the gap, the joint industry project ARISE is conducting a series of field experiments, releasing cold ammonia into the Atlantic

23 Blue ammonia refers to ammonia produced from natural gas with applied carbon capture and storage. Green ammonia, also called e-ammonia, refers to ammonia produced using hydrogen from renewable electricity-powered electrolysis and nitrogen.

Ocean to simulate a bunkering-related spill, collision-related spill, and relief valve opening-related spill, respectively. The results of the experiments will be recorded by specially developed monitoring equipment and published for use by the industry and regulators.

Bunkering

Key findings	
Learnings	• All trials so far successful • Risk assessments results "better than expected" • Refrigerated ammonia bunkering preferred to pressurised, due to better safety profile • Equipment and bunker vessel design requirements being clarified, including emergency release couplings, onboard fenders, etc. • SIMOPs not currently envisaged; no consensus on feasibility • Different views about required bunkering infrastructure, particularly how early dedicated ammonia bunker vessels are required • Community sensitivities could impact the pace of bunkering rollout, requiring close engagement between operators, ports, and communities
Gaps and barriers	• Lack of ammonia bunker vessels over the near-term, with a challenging business case • Ship-to-ship bunkering operation yet to be completed

Ammonia bunkering has followed behind developments in ship and engine design. As such, one interviewee called bunkering "the aspect of the [ammonia] value chain that is least addressed at this point". While progress is being made in this area, interviewees suggested that the industry's understanding of ammonia bunkering remains "at a very first level" and that "a lot more work needs to be done to take [ammonia bunkering] commercial."

Since 2024, 12 ammonia bunkering and transfer trials have been completed across nine locations, shown below. These represent a subset of the 33 ports globally known to be working on ammonia bunkering.[24]

24 *Data from Clarksons World Fleet Register, accessed 16/07/25*

Figure 12: Overview of ammonia transfer and bunkering trials completed as of mid-2025

Sources: Global Maritime Forum compilation, based on desktop research

Truck-to-ship and shore-to-ship bunkering operations have been demonstrated in several locations as part of operational trials for ammonia-powered demonstrator ships. A ship-to-ship bunkering operation is yet to be completed, due to the current lack of large ammonia-capable ships suitable for this. However, four ship-to-ship transfers between ammonia/LPG carriers have been performed and serve as the closest available proxies for ship-to-ship bunkering. These transfers have taken place both in open waters and port environments and reached bunkering-like pumping rates of 800m³/hour.

Interviewees stressed that transfers are not fully equivalent to bunkering operations, which occur more frequently, involve more on-site personnel, and typically happen in environments with nearby receptacles. This gives bunkering a higher risk profile than cargo loading, necessitating more stringent guidelines and comprehensive training.[25] However, they agreed that the trials have progressed the readiness of the ports in question by validating safety and operational protocols and providing important learnings on how to safely and efficiently bunker the fuel.

25 *Global Centre for Maritime Decarbonisation,* "Path to zero-carbon shipping: Insights from ammonia transfer trial in the Pilbara"

Learnings and results

Figure 13: Parameters and outcomes from selected ammonia transfer and bunker trials

	Yokohama (July 2024)	Singapore (March-April 2024)	Ngqura (April 2024)	Pilbara (September 2024)	Rotterdam (April 2025)
Configuration	Truck-to-ship bunkering	Shore-to-ship bunkering	Ship-to-ship transfer	Ship-to-ship transfer	Refrigerated ship-to-ship transfer
Location	Honmoku Wharf	Vopak Banyan terminal, Jurong Island	Moored at Port of Ngqura	Outer anchorage, Port of Dampier	APM terminal, Maasvlakte 2
Stem and duration	Not disclosed	5m^3 (3t) + 6.4m^3 (4.4t)	25.3kt over 11 hours	2x 4000m^3 (2.7kt) 6 hours a piece	800m^3 over 2.5 hours
Outcomes	Provided basis for ammonia bunkering regulations in Japan	Validated Fortescue Green Pioneer's seaworthiness, propulsion systems, and manoeuvrability	Demonstrated the feasibility of ship-to-ship ammonia transfers	Set anchorage zone for ammonia bunkering, generated recommendations for ABV design	Validated Rotterdam's ammonia safety framework, paving the way for case-by-case ammonia bunker operations

Source: Global Maritime Forum compilation, based on desktop research

The trials have leveraged risk assessments, the results of which were characterised by one interviewee as "better than expected". For example, in preparation for an ammonia bunkering trial in the Pilbara region of Australia, the Global Centre for Maritime Decarbonisation (GCMD), Yara Clean Ammonia, and Pilbara Ports carried out detailed HAZID and HAZOP assessments that did not identify any high risks stemming from the operation. Meanwhile, an external safety study performed by Port of Antwerp-Bruges found that it could be safe to bunker ammonia in 50% to 70% of berths in the two ports, viz. Antwerp and Zeebrugge, depending on the conditions.[26] It is expected that ships calling these berths will make up most of the demand for ammonia bunkering.

These studies have been used to identify the best locations for ammonia bunkering at the ports in question. In the case of the Pilbara, dispersion modelling completed in preparation for the trial found that any ammonia cloud resulting from a leak would travel no more than one nautical mile. This falls within the diameter of the outer anchorages at Port Dampier, where ammonia bunkering is expected to take place, meaning a leak should not affect the safety of other ships in the port. At the same time, Port of Amsterdam stressed that the risks posed by a leak would be higher for city ports.

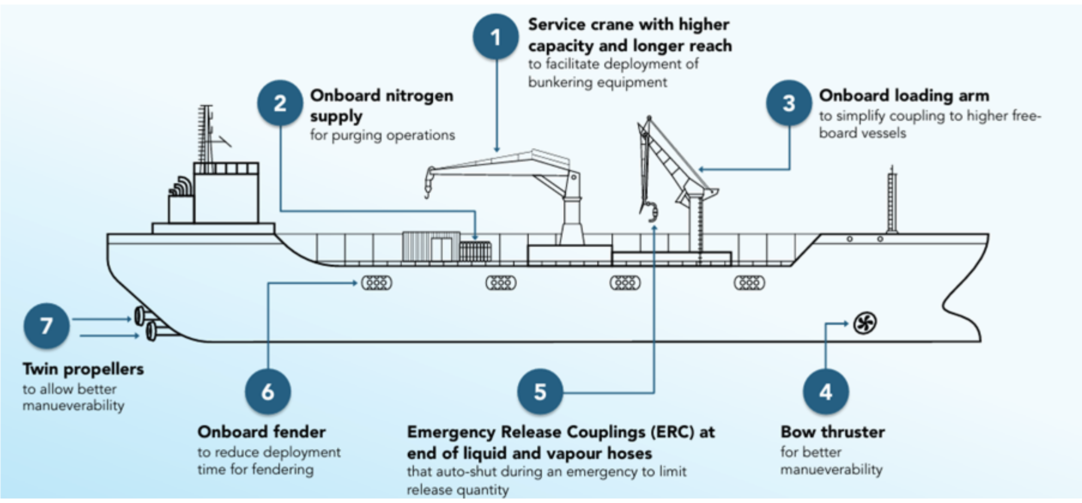
26 This includes the bunkering configuration, the volumes of fuel bunkered, and pumping rates among other things.

Another key output has been the development of the first emergency response plans for potential ammonia bunkering incidents. BHP, which is studying the practicalities of ammonia bunkering, drew attention to some of the risks that must be addressed in this regard, with an assessment showing that "an emergency situation on the bunkering vessel can create an emergency situation on the receiving vessel". In particular, "one of the biggest issues we identified was that if the bunkering vessel vents in the event of an emergency, [due to] the height difference between the two vessels, the vented ammonia could go towards the receiving vessel."

Multiple interviewees reported that bunkering refrigerated (-33° Celsius), rather than pressurised, ammonia is the safest and most viable approach. Port of Rotterdam emphasised this as a key finding from its safety studies. The trial at the Port of Rotterdam also identified a risk that nitrogen could enter one of the ship's ammonia tanks as a result of purging, causing a malfunction in the ship's boil-off gas management system. An ammonia release mitigation system is thus required.

Finally, the trials have generated insights about the design and equipment required on future ammonia bunkering vessels. GCMD noted that while the ammonia transfers in the Pilbara trial took around 13 hours, the full trial took five days. This was because the equipment required for ammonia transfer was not available on the ammonia carriers and instead had to be brought on board by a separate supply vessel. Considering the time constraints on future bunkering operations, ammonia bunker vessels will need to be equipped with the necessary hardware. This includes, among other things, onboard nitrogen supply to conduct leak tests prior to—and purge after—bunkering, onboard fenders, and emergency release couplings to automatically seal the transfer system in case of a hose separation.

Figure 14: Suggested hardware and design elements for ammonia bunker vessels



Source: Global Centre for Maritime Decarbonisation

Remaining gaps

At the same time, several elements need to be addressed to enable the first wave of ammonia-powered ships between 2026 and 2027, and beyond.

There is broad agreement on the lack of suitable bunkering infrastructure. The availability of suitable ammonia bunker vessels is considered the biggest challenge. Specifically, it is uncertain whether interim solutions enabling bunkering on a case-by-case basis in the early days of the fuel's adoption are desirable. Indeed, ports reported that this makes it hard to undertake true-to-life demonstrations.

One interim solution would be to use existing ammonia barges. However, they typically transfer pressurised rather than refrigerated ammonia. Given refrigerated ammonia is expected to be the norm, these barges would not be testing guidelines and procedures for real-world bunkering nor following emerging best practices.

An alternative is to charter a small or medium-sized gas carrier capable of transferring refrigerated ammonia. However, multiple interviewees pointed to the logistical difficulties associated with this, given these vessels are "in very high demand in the market" and "not necessarily where you would want them". This is expected to create planning challenges and be costly. As such, while this may be an option on an ad hoc basis, for example, once or twice a year, "as soon as we start to scale up [to 4-5 bunkering events per year], a bunker vessel needs to be there."

This has prompted discussions about whether moving directly to long-run solutions, namely dedicated ammonia bunker vessels, makes more sense. However, this presents challenges of its own. Assessments performed by first movers show that ammonia bunker vessels are expensive investments that need to achieve high levels of utilisation to be viable. At this stage in the development of the ammonia bunker market, demand for these vessels is limited. In parallel, there is a timing challenge, with it being "unlikely that [many] bunker vessels will be ready [...] for the first few bunkerings in 2026 and 2027", since this represents a tight window for designing and building such a vessel. One 5,000m^3 ammonia bunker vessel has been ordered to date by Japanese conglomerate ITOCHU, which will be deployed in Singapore from late 2027. Further vessels that could be deployed in the near future would likely need to leverage existing designs, of which there are at least ten under development, according to data from the Ammonia Energy Association.

Copenhagen Infrastructure Partners: Kickstarting ammonia bunkering in Europe

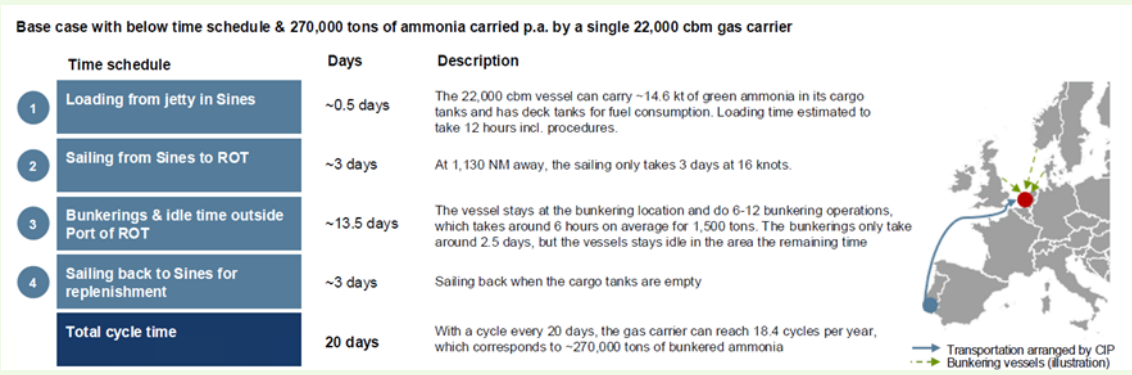
Investment fund Copenhagen Infrastructure Partners (CIP) is one of the world's biggest clean ammonia developers. It is seeking to supply clean ammonia to shipping, having won EU and Australian government funding to support the development of several projects aimed at the maritime market.

The fund plans to not only produce the molecule, but provide end-to-end solutions, including bunkering. Within Europe, CIP is aiming to supply up to 200,000 tonnes of e-ammonia in the Amsterdam-Rotterdam-Antwerp (ARA) region by 2029. This will see green ammonia produced at its Madoqua project in Sines, Portugal, transported to the ARA region by a 22,000m³ ammonia-capable ammonia carrier, where it will be loaded onto a smaller gas carrier for bunkering at anchorage outside the ports. CIP pointed to several advantages with this solution.

First, since floating storage is provided by the ammonia carrier, there is no need to build extra storage at the bunker ports. This is especially beneficial in Europe, where the timeline and cost of building new storage is expected to be significant.

Second, performing the bunkering at anchorage presents fewer safety risks than bunkering within the port environment. While it means SIMOPs will not be possible, using gas carriers allows a loading arm to be used rather than a bunker hose. This reduces crew involvement and the amount of time needed to connect and disconnect, while increasing the pumping rate of the fuel. As such, CIP said that it should be possible to safely bunker a large container ship in six hours, rather than the 12 hours generally anticipated. The company believes this will make bunkering at anchorage acceptable to ship operators.

Figure 15: Overview of CIP proposed ammonia bunkering solution in Rotterdam



Source: Copenhagen Infrastructure Partners

In terms of the business case, CIP underscored the importance of achieving high utilisation of the vessels, with optimal utilisation estimated to reduce the cost of delivery from around $80 per tonne to just $35 per tonne. Doing all bunkering at anchorage creates a centralised point for supplying different shipping segments, helping to aggregate demand. Meanwhile, CIP envisages using idle time to supply industrial ammonia offtakers at the existing chemical clusters in ARA, further boosting utilisation.

To operationalise the solution, CIP has signed MoUs with Faerder Tankers and BW Epic Kosan to develop and charter an ocean-going ammonia-fuelled ammonia carrier and mid-sized ammonia-fuelled ammonia carrier respectively. In parallel, it has developed a 73-page Ammonia Bunkering Operations Manual with class society American Bureau of Shipping, providing safety protocols for ammonia bunkering operations.

Interviewees suggested that "the port acceptance part of this value chain is huge" and that there are stark differences in the knowledge levels and risk appetites across different ports and terminals. One operator characterised it as moving from a situation where ships go to a port "and the port says yes or no" to bunkering to one in which "if we go to them for approval for bunkering these vessels, we need to work hand in hand with them to develop the capabilities, the procedures, and so on." While this is common in the early adoption of new fuels, the scale of the challenge is expected to be greater for ammonia than its alternatives, because the fuel is "so much more sensitive in the community". The operator suggested that a highly proactive approach is needed, with first mover operators and ports collaborating closely.

Container liners and car carriers interviewed continue to consider SIMOPs "non-negotiable," highlighting this as a factor slowing the fuel's uptake in these segments. There is no clear consensus on this at present; while some ports are considering SIMOPs trials as early as next year, other actors working in the space suggest that SIMOPs remain "five years away," if they are feasible at all.

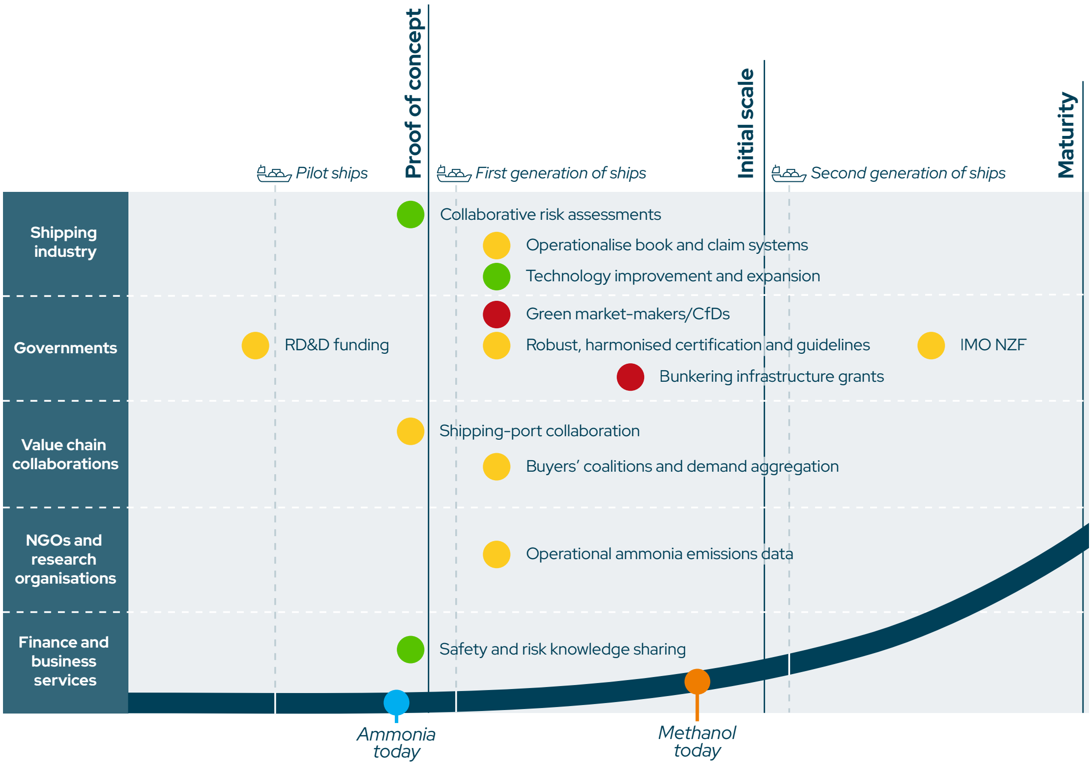
Conclusions and recommendations

The findings of this report show that both fuels are now ready—methanol for low-carbon operation and ammonia for piloting. This represents a significant maturation since the release of the first Getting to Zero Coalition Mapping of Zero-Emission Pilots and Demonstration Projects in 2020, which summarised the state of play at that time by noting that "there have recently been a number of projects launched looking into the potential of hydrogen-based fuels such as green ammonia or green methanol for deep-sea vessels". Far from merely being a matter of potential, this report has shown that methanol and ammonia shipping fuels are becoming a reality.

The next milestones on the fuels' journey to maturity are clear. For ammonia, moving beyond proof of concept and towards initial scale will involve successfully piloting the first wave of ammonia-powered ships, finalising and scaling up ammonia engine production, validating the safety of ammonia bunkering operations, and introducing low and zero-carbon ammonia molecules. For methanol, progressing into initial scale and beyond will involve increasing use of green methanol in a growing fleet of newbuild and retrofitted vessels, underpinned by the availability of bunkering at a critical mass of key ports across the globe.

Efforts to meet these milestones are underway, but a further push is needed if the fuels are to reach maturity around 2030 in line with the industry's targets. Future efforts should address the remaining gaps (see orange and red in Figure 16) and focus on two main areas: accelerating the development of the fuel supply chain and keeping the technology and design developments on track, while ensuring safety and climate benefits.

Figure 16: Proposed actions to accelerate the maturation of methanol and ammonia by the required time of implementation and implementation status



Source: Adapted from [RMI's 'A Theory of Rapid Transition'](); *proposed actions and status based on expert interviews. Red = critical gap; orange = further efforts needed; light green = enhanced efforts beneficial*

Accelerating the development of the fuel supply chain

Scaling green methanol and ammonia availability

The limited availability of low- and zero-emissions versions of methanol and ammonia is a key challenge. This is not due to a lack of supply projects but rather continued difficulties in signing the long-term offtake agreements required to realise them and thereby access the fuels. This is itself driven in significant part by the cost gap for using green methanol and ammonia.

Further **clarity around the shape of the IMO Net Zero Framework**, agreed in April 2025 but still awaiting the finalisation of key parameters affecting the business case for e-fuels, is eagerly awaited. However, interviewees also stressed the strong complementary role of national/regional governments and cargo owners.

In terms of national/regional government support, several major shipping nations and blocs now offer funding for maritime decarbonisation RD&D, including the EU, the UK, Norway, Japan, and others. However, these schemes generally focus on feasibility studies and/or the capital costs of investing in zero-emission ships. With the first ammonia-capable ships soon to hit the water, early movers see opportunities for national/regional governments to **channel future RD&D funding towards operational pilots**, especially offsetting the increased fuel costs associated with these pilots. Beyond RD&D funding, many interviewees pointed to **green market-maker schemes**, like H2Global, and **Contracts for Difference** as promising mechanisms for national/regional governments to increase the availability of green methanol and ammonia.

In parallel, early movers are looking at ways to capitalise on the demand some cargo owners have for low- and zero-emission shipping. Some operators are using commercial innovation to harness this demand. This includes Wallenius Wilhelmsen, which is introducing a re-engineered bunker adjustment factor to pass through the cost of alternative fuels to customers. Many interviewees, both within and beyond the container sector, highlight the Zero-Emission Buyers' Alliance as a key mechanism for effectively channelling this demand. It has also been suggested that **book-and-claim systems** should be further adopted to resolve mismatches between the location of cargo owners willing to pay a premium for low-carbon shipping and the best locations for bunkering the fuels, particularly given the growing importance of China as a production location for green methanol and ammonia.

Establishing bunkering infrastructure

True-to-life ammonia bunkering demonstrations and the rollout of commercial methanol and ammonia bunkering are being hindered by the poor investment case for bunker vessels. This is because bunker vessels are expensive assets that rely on high levels of utilisation, which are difficult to achieve at this stage in the development of the methanol and ammonia bunker markets.

Many interviewees highlighted the potential for **fuel demand aggregation** to help address the issue. Despite widespread agreement about the need for demand aggregation and growing awareness about the approaches for doing so, there remain few examples in practice. There is a need to operationalise fuel demand aggregation, particularly at major bunkering hubs—both existing and emerging—and on green shipping corridors, where there is likely to be more demand to aggregate.

Alongside this, **CAPEX grants** are considered an impactful and realistic way for national/regional governments to support the development of methanol and ammonia bunkering infrastructure. By reducing the levels of investment required, grants can improve the business case for bunker vessels. The sums needed to have a meaningful impact—in the tens of millions of dollars range—are likely manageable and should generate the provable local socio-economic benefits that are important in justifying the use of taxpayer money. Funding of this sort is currently lacking, with one notable exception being Spanish energy company Moeve, which has received just over €30 million from the EU to develop ammonia and methanol bunkering infrastructure at the ports of Algeciras and Huelva respectively, including bunkering vessels.

Interviewees stressed that the smooth introduction of methanol and ammonia bunkering requires **closer collaboration between ports, terminals, and ship operators**. One suggestion was to identify the routes where operators are looking to deploy methanol and/or ammonia-powered ships, engage the relevant ports and terminals to understand their readiness for bunkering methanol and/or ammonia, and undertake any safety studies and/or bunkering pilots required to clear the path. These efforts could take place in the context of a green shipping corridor initiative, particularly if fuel demand aggregation is also being scoped.

Keeping technology development on track

Interviewees highlighted the need for further **engine sizes and types, increased availability of spare parts, resolution of technology teething problems, and reductions in the lengthy timelines and high cost of retrofits**. Efforts are ongoing by engine manufacturers and shipowners to tackle the first two of these issues, while timelines and costs for retrofits can be expected to decrease as more projects are completed and experience grows. Similarly, a lack of understanding regarding the consequences of and mitigating actions related to ammonia spills at sea is set to be filled by the ongoing ARISE project.

Uncertainties remain about the onboard emissions associated with burning ammonia. This is partly because engine manufacturers are waiting for the IMO to complete its life cycle emissions guidelines before finalising the design of their ammonia dual-fuel engines. This makes a **timely and robust outcome from the IMO life cycle emissions guidelines** process important to ensure that the engines perform to their potential. This will depend on the availability of quality data about the engines' emissions profile. In this regard, interviewees suggested there would be value in **independent studies measuring the operational emissions from the first wave of commercial ammonia-powered vessels**. No such studies have been publicly announced at present.

Fuel certification is also a challenge. Mismatches between different national regulatory frameworks slow down fuel project development while creating compliance risks and greenwashing accusations for potential offtakers. Interviewees again pointed to the importance of a robust and timely outcome from the IMO life cycle emissions guidelines as a solution.

Finally, shipowners and operators emphasised that designing methanol and ammonia-capable ships is a time- and resource-intensive undertaking. **Knowledge sharing initiatives** could reduce the burden, accelerate the pace of developments, and maximise safety. Two sets of stakeholders are seen as well-placed to act:

- **Shipyards** building multiple methanol and/or ammonia-capable vessels could bring the different shipowners together in collaborative HAZID and HAZOP exercises. In parallel, they should iterate methanol and ammonia-capable ship design as far as possible to ensure progress is being built upon.

- **Marine insurers**, through their work to assess risks and analyse safety incidents, will likely have strong insights into the safety of methanol- and ammonia-capable ships. Given their industry contact networks, they could undertake ad hoc convenings or establish a standing initiative to help disseminate safety and risk-related information about the fuels within the sector.

Appendix: Summary of key learnings, gaps and barriers, and proposed actions

Methanol

Area		Learnings	Gaps and barriers	Proposed actions
Ship design and technology	Newbuilds	• Engine and fuel supply systems suitable for most ships available • Fuel and bunkering systems generally working well, but with teething problems around the engine, including issues with switching fuel and high maintenance requirements. • Relatively minor design changes required for safety management, e.g. location of accommodation, and design of venting and firefighting systems • Lower energy density not a showstopper, but creates a trade-off, usually bunkering twice as frequently • Synergies available on some ship types e.g., RoPax and car carriers	• Ship design process time and resource-consuming	• Knowledge sharing initiatives
Ship design and technology	Retrofit	• Significant undertaking, but feasible and more economical than retrofits to other main alternative fuels • Minor changes to tanks and engines, but possible need to extend vessels	• Lead times for retrofits currently long and costs high • Limited availability of suitable yards for retrofit projects	
Crew		• Crew training required, but not especially complex or long • Positive perceptions of the fuel among seafarers • Bottleneck encountered in the availability of training, but ecosystem of training providers now in place		
Operations	Bunkering	• Bunkering operations similar to fuel oil, with the smallest safety distances of the main alternative fuels and proven SIMOPs • Ability to use conventional bunker barges with limited modifications, but dedicated methanol bunker vessels are also emerging • Positive perceptions of the fuel among port stakeholders • Mostly grey methanol bunkered to-date • Sufficient green methanol supply is available, with China leading developments	• Offtake challenge, due to premium, long-term fixed price commitment, certification and geopolitics • Bio-methanol currently offers 65-70% emissions reductions - below its potential • Challenging business case for dedicated methanol bunker vessels, including retrofitted conventional vessels	• Clarity on the IMO Net Zero Framework, especially rewards • Demand pull policies from national/ regional governments, such as green market-makers or Contracts for Difference • Operationalise fuel demand aggregation • CAPEX grants for bunkering infrastructure • Use book and claim systems

Ammonia

Area		Learnings	Gaps and barriers	Proposed actions
Safety	Ship design	• Significant design changes needed: › Segregating sections for leak safety and no venting under any circumstances emerging as guiding design principles › Package of safety measures and technologies required, e.g., double-wall piping, additional gas detectors, remote stop, automation, increased ventilation, refrigeration, and water sprays/curtains • Challenge around safely and efficiently managing boil-off gas due to lack of suitable auxiliary engines	• Ship design process time and resource-consuming	• Knowledge sharing initiatives
	Crew	• Mixed but manageable response from seafarers to working on first ammonia ships • Life onboard expected to be broadly similar, but more complex • Hands-on experience and learnings from ammonia carriers being incorporated into training		
Emissions	Engine and fuel system	• 90-95% tank-to-wake emissions reduction likely to be possible: • Ammonia slip and nitrogen oxide emissions expected to be IMO compliant: • Engine emissions highest for four-stroke engines and at lower engine loads • Two emissions abatement technologies required - ammonia release mitigation system and selective catalytic reducer	• Lack of some engine sizes, particularly suitable auxiliary engines and main engines for large containerships, as well as ammonia boilers • Real-world emissions profile still uncertain; data from ammonia-powered ships required	• Independent studies to measure real-world emissions from early ammonia-powered vessels • Timely and robust IMO lifecycle emissions guidelines
	Operational emissions	• First ships not expected to achieve full emissions reduction potential immediately: › Fuel will initially be used 25-50% of the time to test systems › Conventional auxiliary engines are often retained; ammonia not used within ports or when manoeuvring › Blue ammonia likely to be used, particularly early in ammonia's introduction	• Lack of understanding around ammonia spills at sea	

Bunkering	Safety and procedures	• All trials so far successful and risk assessments results "better than expected" • Refrigerated ammonia bunkering preferred to pressurised, due to better safety profile • Equipment and bunker vessel design requirements being clarified, including emergency release couplings, onboard fenders, etc • SIMOPs not currently envisaged; no consensus on its feasibility	• Ship-to-ship ammonia bunkering operation yet to be completed	
	Port readiness	• Different views about required bunkering infrastructure, particularly how early dedicated ammonia bunker vessels are required • Community sensitivities could impact on the pace of bunkering rollout, requiring close engagement between operators, ports, and communities	• Lack of ammonia bunker vessels over the near-term, with a challenging business case	• Clarity on the IMO Net Zero Framework, especially rewards • Demand pull policies from national/ regional governments, such as green market-makers or Contracts for Difference • Operationalise fuel demand aggregation • CAPEX grants for bunkering infrastructure • Use book and claim systems • Pursue deeper collaboration between ports, terminals, and first movers