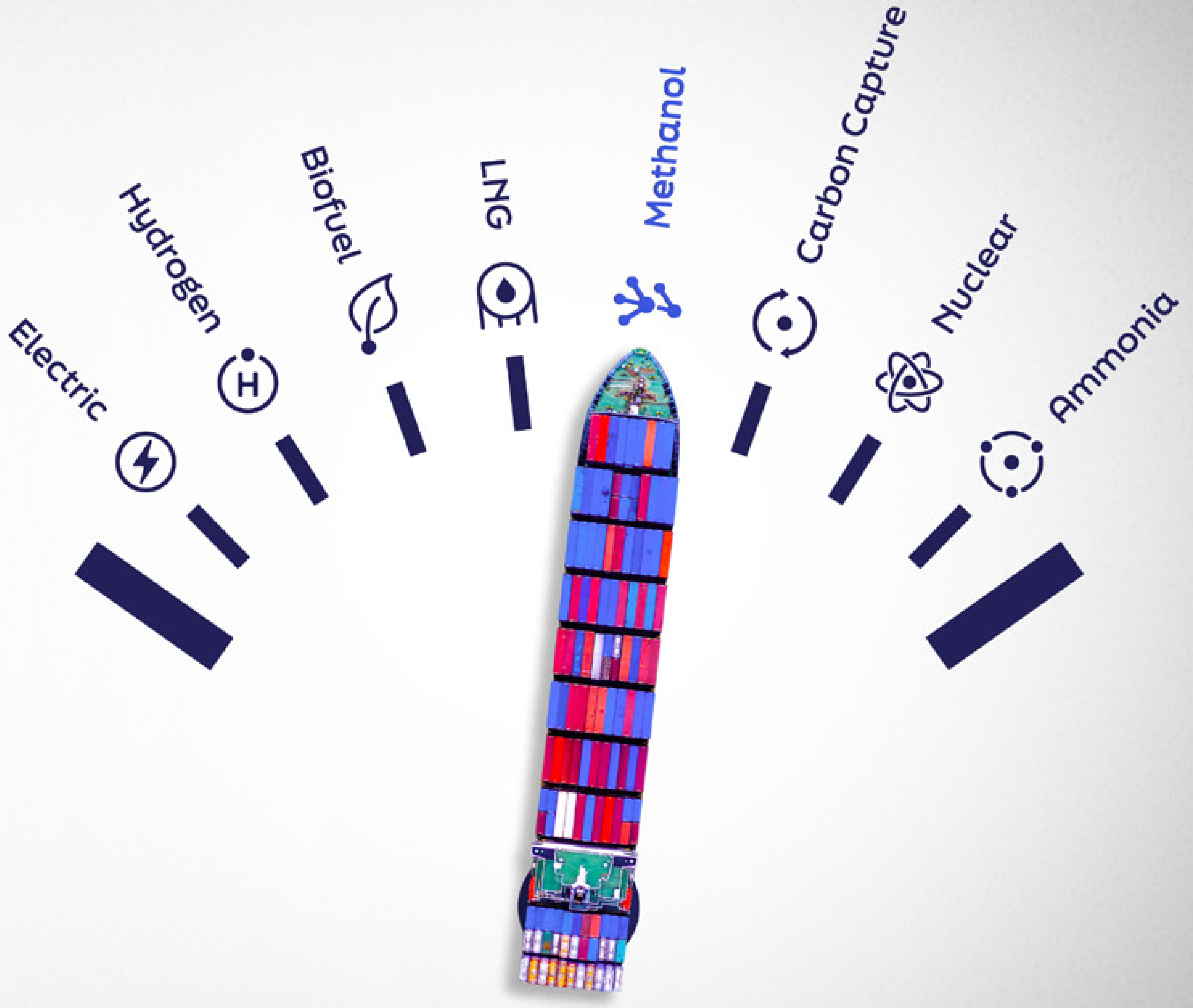
FUEL FOR THOUGHT
Methanol



Expert insights into the future of alternative fuels

Your trusted adviser in alternative and low carbon maritime fuel

Contents

Preface

The challenge of maritime decarbonisation is not that it is happening, but that it is happening so quickly.

The evolution of sail to its heyday of the great tea clippers took centuries, and the transition to coal-powered steam ships was driven by greater supply chain mobility and speed. The arrival of diesel-fuelled engines led to a new type of vessel propulsion, but took nearly a hundred years to emerge. Each shift had a dramatic impact on the cost, speed and efficiency of shipping.

The energy transition the maritime industry faces today is distinct from those earlier evolutions. It is not driven by technological advances or economics, but by an environmental imperative – increasingly underscored by social pressure, policy and regulatory demands to reduce emissions.

Decisions are being made today without clear market certainty, but in the knowledge that regulations rather than economics will push forward change. In this context, shipowners, charterers, insurers, financial markets and technology suppliers are seeking a better understanding of where the industry is heading.

Lloyd's Register is committed to providing trusted advice and leading the maritime industry safely and sustainably through the energy transition. Our new Fuel for Thought series puts decarbonisation options under the spotlight, analysing policy developments, market trends, supply and demand mechanics and safety implications.

Each edition focuses on a specific fuel or technology, creating a reference point for the industry to overcome upcoming challenges as it faces the next great shift in ship propulsion.

This first Fuel for Thought focuses on methanol, a regularly produced chemical and fuel that is moving towards green production, providing one possible answer to the challenges faced by owners and operators.

Future editions of the Fuel for Thought series will examine ammonia, biofuels, carbon capture technologies, nuclear power, hydrogen, battery and electric power and the transition of LNG.

1.1

Chapter 1: Introduction

Introduction from the Methanol Institute (Chris Chatterton, Chief Operating Officer, The Methanol Institute)

Behind its high degree of acceptance by shipowners, lies years of work to prove and improve on the concept of methanol as a marine fuel.

The decision by more and more leading shipping companies to adopt methanol as fuel is a signal. It shows that the industry recognises the need to start its transition to net zero now, first lowering carbon and progressively achieving net carbon neutral operations.

If investment decisions are delayed in the hope that yet unavailable fuels will emerge quickly then the industry will find itself in no better place. Indeed, emissions will likely rise while the transition will be further delayed.

Shipowners are recognising that methanol provides them with flexibility in introducing a low-pollution, lower carbon fuel which is closest to a drop-in available in the market. This means lower upfront capex and opex costs compared with the current fuel choices.

Methanol supports compliance towards the IMO's 2030 carbon emission reduction target and critically provides a pathway towards net carbon neutral operations.

The Methanol Institute (MI) believes this will be a phased transition, requiring significant levels of collaboration and application of fuel, technology, infrastructure and people across the supply chain. MI believes we will need to leverage conventional lower carbon marine fuels to meet current and proposed IMO carbon intensity targets and net carbon neutral shipping operations. This includes biofuels, intermediate blue and ultimately renewable green fuels, together with carbon capture technology.

1.2

Methanol fact file

What is it? CH_3OH

Methanol, also called methyl alcohol, is a light, volatile, colourless and flammable liquid alcohol. Its name comes from its early derivation from methane, which is a significant feedstock in today's fossil-based methanol production (see section 4.1 on methanol production routes). Each methanol molecule has one carbon atom and four hydrogen atoms, and it is the simplest alcohol.

Methanol has certain characteristics that make it a suitable marine fuel. It is a liquid at ambient temperatures and pressure, and can be stored in modified fuel tanks on existing vessels. The three main drawbacks to its use are its toxicity, its low energy density – with about 225g providing the same amount of energy when combusted as 100g of gasoil – and its low flashpoint, contributing to increased fire and explosion hazards.

Methanol burns cleanly compared to conventional fuel oil. There is little sulphur content in the fuel, resulting in no sulphur oxides forming during combustion. Particulate matter and soot emissions are also low.

Methanol is lighter than water, but also highly miscible (soluble), so the fuel will rapidly dissolve in seawater in the event of a spill.

It is a widely manufactured, used and transported chemical. The following tables offer insight into its properties, including the advantages and disadvantages of it becoming a marine fuel. Methanol has identical properties regardless of how it is manufactured, meaning the combustion opportunities and challenges are the same too.

There are many different types of methanol, classified by the methods of production, i.e. from fossil fuel or renewable sources etc. For the full list, please refer to annex 5.

Methanol combustion formula

$$2CH_3OH + 3O_2 \rightarrow 2CO_2 + 4H_2O$$

In an internal combustion engine methanol reacts with oxygen in the air and creates carbon dioxide and water as well as heat/energy.

Properties table

Flash point	12°C (54°F) (closed cup, 1 atmosphere)
No sulphur (SOx)	and no sulphate particulate matter
Density	Liquid: 0.79 g/cm³ at 68°F/39°F (20°C/4°C)
Flammability	6% to 36% volume percentage
Energy density comparison	1,000 cu m MDO = 2,400 cu m methanol

For full list see annexes here

Advantages and disadvantages of methanol

The following table offers a brief insight into the benefits of using methanol as a marine fuel and the challenges.

Advantages and potential	Challenges and issues
Current high availability due to industrial use (but not green)	Corrosive: requires specific storage and handling arrangements
Liquid at ambient temperatures and pressure	Low flashpoint and toxicity – need increased safety systems
Miscible in water (biodegradable)	Lower energy density compared to fuel oil
Low emissions compared to existing marine fuels (when viewed on a life cycle basis)	Onboard combustion creates GHG (1kg methanol combusts and forms 1.375kg CO_2) but mitigated under proposed life cycle assessment criteria
Regulations and market maturity	Green production needs significant increase to meet potential demand
Life cycle emissions potential	Uncompetitive price point relative to standard fuel oil

1.3

Readiness of methanol as a marine fuel

Lloyd’s Register has collaborated with industry stakeholders to build a comprehensive assessment of different aspects of the fuel supply chain from production to delivery onboard, and the technologies for use as a fuel onboard for power generation.

The main production methods for future methanol supplies for the maritime industry are described in Chapter 4, while Chapter 5 details the status of various onboard technologies.

Lloyd’s Register’s Maritime Decarbonisation Hub has already developed a framework to measure the current readiness of several fuels in its Zero-Carbon Fuel Monitor publication.

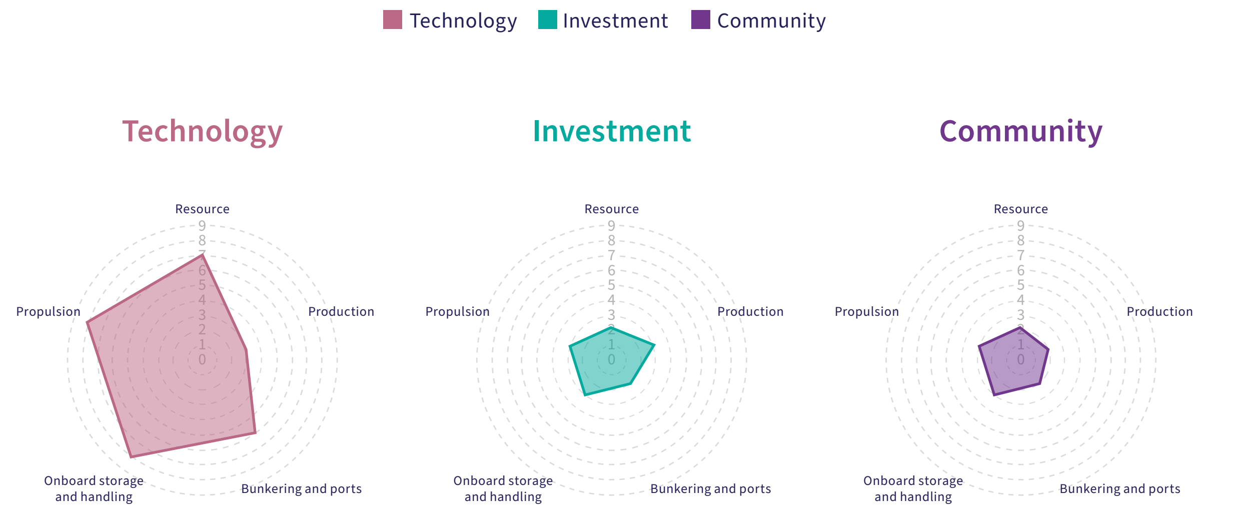
A lot of focus is often put on technology readiness level (TRL) of new technology but this is just one element. The industry’s willingness to adopt a technology is also based on its investment readiness level (IRL), which signifies whether the business case is hypothetical or well proven. Community readiness level (CRL) is also crucial, identifying whether the frameworks for safe and publicly acceptable use of a technology and fuel are in place. TRL is assessed on a scale of one to nine, IRL and CRL are on a scale of one to six.

LR uses the outputs of the monitor to identify research, development and deployment projects that will advance solution readiness and accelerate a safe and sustainable transition to net zero GHG emissions.

The detailed information from this assessment reveals how the technology for producing, delivering, and combusting blue or green methanol are well advanced. However, the level of investment required is still lacking and the acceptance within the maritime and client communities is also low.

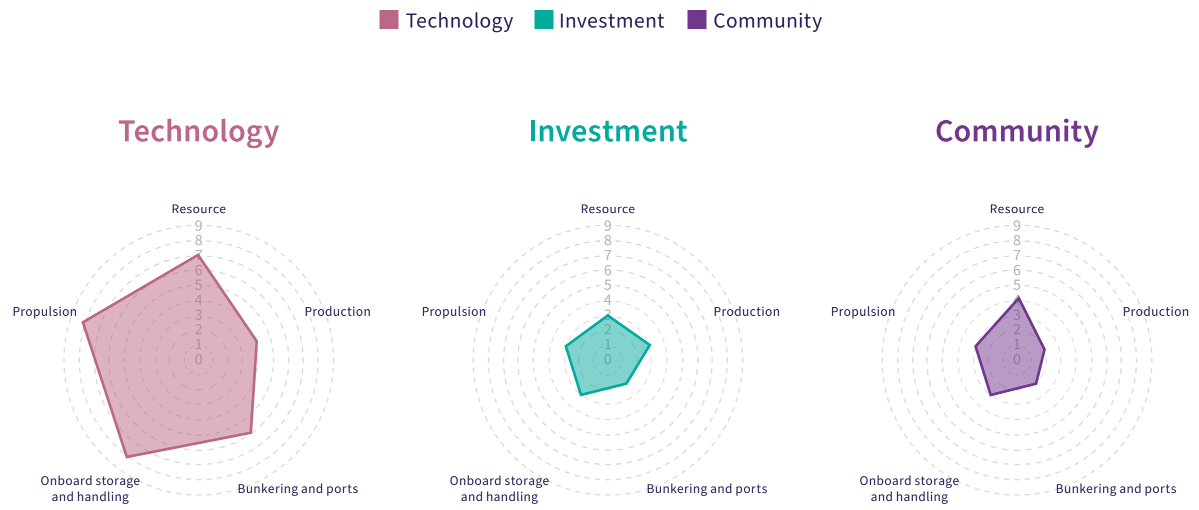
Definitions of the IRL, TRL and CRL levels can be found in Annex 1.

Bio-methanol



Technology Readiness Levels (1–9), Investment and Community Readiness Levels (1–6)

Green methanol



Technology Readiness Levels (1–9), Investment and Community Readiness Levels (1–6)

2.1

Chapter 2: General safety and toxicity issues

Introduction

Methanol is toxic and extreme care is required with handling. It can be absorbed into the body by inhalation, ingestion, skin contact, or eye contact. Adverse health effects of methanol contamination or exposure are not always immediately evident and can be fatal. The fuel will also react violently with strong oxidants, raising the risks of fires and explosions in the case of a leak.

It has a flash point of **12 °C**

a lower explosive limit in air **of only 6%**

and an upper limit **of 36%**.

Methanol evaporative vapours may be heavier than air, causing them to spread along the ground and collect and stay in poorly-ventilated, low-lying, or confined areas, such as engine room bilge areas.

There are numerous safety guidance publications as methanol is a regularly used chemical feedstock and maritime cargo. There are also preliminary guidance notes for parties wishing to determine an approach to methanol bunkering from a port, ship's crew or bunker supplier perspective including Lloyd's Register's 'Introduction to Methanol Bunkering Technical Reference'.

Hazards and precautions guidance:

FLAMMABLE	Methanol is flammable and burns with a clear blue flame that is smokeless and difficult to see in daylight. Keep away from sources of ignition including heat, sparks, flames, and hot surfaces. Keep containers tightly closed when not in use. Containers should be stored in well-ventilated and cool areas.
HEALTH	Methanol can be toxic if swallowed, inhaled or contacts the skin, although skin absorption is a slower process than ingestion or inhalation. Avoid breathing vapours or mist. When handling methanol, wear chemical-resistant gloves and appropriate PPE. Depending on the activity, respiratory protection may be required. If swallowed, immediately seek medical attention.

2.2

Specific bunkering considerations

Methanol is a liquid at ambient temperature and pressure. Unlike ammonia, hydrogen, ethane, LPG and methane (natural gas) it does not need to be pressurised, compressed or stored cryogenically. However, methanol is corrosive and storage tanks need to be constructed from a compatible material or appropriately coated.

As per the IMO's requirements for ships using methanol, the bunker tank ullage space should also be inerted with a gas such as nitrogen gas to reduce explosion risks and vessels may need inerting systems installed. Fuel systems need to be considered in a retrofit or newbuild design given lubricity issues.

Lloyd's Register and the Methanol Institute developed robust guidance on methanol bunkering processes in 2020 with the publication of the Introduction to Methanol Bunkering Technical Reference. The Methanol Institute has also regularly updated its The Methanol Institute Safe Handling Manual (4th edition).

Potential methanol bunker suppliers, ports and users should also be aware of work of the CEN Workshop Agreement in Europe. CEN, the European Committee for Standardization, is one of three bodies recognised by the European Union as being responsible for developing and defining voluntary standards at European level. The methanol bunkering workshop agreement was in partnership with industry actors including Lloyd's Register and the Methanol Institute.

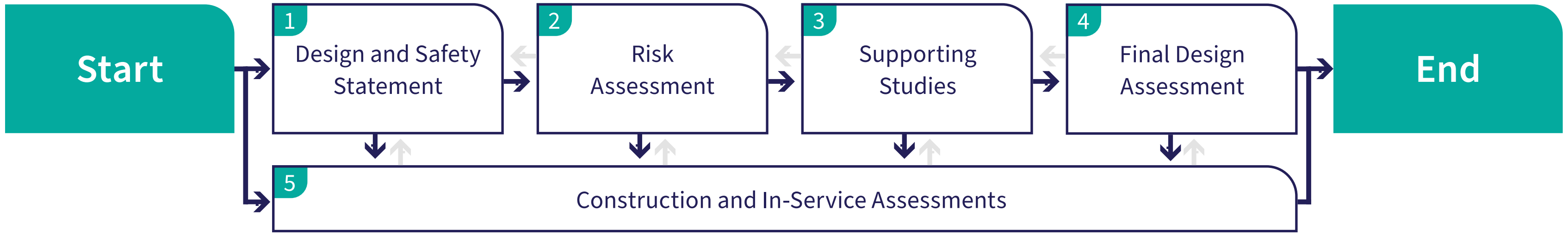
For inland waterways specifically, the European Committee for drawing up Standards in the field of Inland Navigation (CESNI) has developed standards for inland waterway vessels (ES-TRIN), Edition 2021/1.

Additionally BS EN 60079-10-1:2015 exists to cover explosive atmospheres (Part 10-1: Classification of areas – Explosive gas atmospheres) and Lloyd's Register's gas-fuelled ship rules, IGF Code and MSC.1/Circ.1621 specifically refer to IEC 60079-10-1.

The development of any new bunker supply chain requires diligence and full risk assessments to ensure it is safe for all users and bunkering conditions. The aforementioned methanol bunkering technical reference supports the bunkering process and the IMO published a circular in 2020 for ship and bunkering requirements. See: IMO circular (IMO, MSC.1/Circ. 1621) Interim Guidelines For The Safety of Ships Using Methyl/Ethyl Alcohol as a Fuel.

However, it is worth noting that similar ISO standards that have been developed for LNG bunkering are currently not in place.

LR Risk Based Certification Process (for new, novel and alternative designs)



Lloyd's Register's requirements for Ships Using Methyl Alcohol (Methanol) or Ethyl Alcohol are contained within Appendix LR1 to the Rules and Regulation for the Classification of Ships Using Gases or Other Low-flashpoint Fuels, and which incorporates MSC.1/Circ.1621. These requirements follow a risk-based approach where the fundamental requirement is to demonstrate an equivalent level of safety to that achieved with conventional oil-fuelled systems.

The risk-based process is to be undertaken in accordance with LR's ShipRight Procedure for Risk Based Certification (RBC). It is based on IMO guidance and LR's experience of how a safety justification can inform the normal rigors of ship classification.

Importantly, the process is scalable. This means the amount of work required in each step is proportionate to the risk presented.

2.3

Methanol bunker quality

Methanol bunker quality standards are currently under development. A group at ISO – working on ISO 6583: Specification of methanol as a fuel for marine applications – has developed guidance that is due for final delivery in 2024.

An existing methanol specification is also available from IMPCA, the International Methanol Producers and Consumers Association. IMPCA has also published a draft sampling standard and has a tool to help determine CO_2 footprint/life cycle calculation for methanol depending on its feedstock and eventual use (fuel or chemical etc.).

2.4

Summary

Shipping has considerable experience with methanol as a cargo. Currently methanol is shipped globally under a regulatory framework that includes MARPOL Annex II (Regulations for the control of Pollution by Noxious Liquid Substances), the IBC Code and IMDG Code. As a fuel, there is guidance from the IMO with the goal-based approach of the IGF Code. In particular, the interim circular (MSC.1/Circ. 1621) with interim guidance for the safety of ships using methanol (methyl alcohol) as a fuel.

Bunkering safety is also covered at a European level through the CEN workshop, and additional guidance from a classification perspective comes from the LR bunkering requirements and class notations.

Fuel quality is also covered with the IMPCA methanol reference specifications, and under development at the ISO (ISO 6583).

Methanol as a fuel/methanol as a cargo regulatory framework

Methanol as a cargo	Methanol as a fuel	Industry standards
Annex II of MARPOL 73/78 – Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk	International code of safety for ships using gases of other low-flashpoint fuels (IGF Code)	IMPCA methanol reference specifications
International Code for the Construction and Equipment of Ships carrying Dangerous Chemicals in Bulk (IBC Code)	Interim Guidelines for the safety of ships using methyl/ethyl alcohol as a fuel (IMO MSC.1/Circ. 1621)	ASTM D-1152/97: Standard specification for methanol
IMDG Code (Class 3, Cat B, UN No.1230)	Lloyd's Register: Classification of ships using gases or other low-flashpoint fuels	ISO/AWI 6583: Specification of methanol as a fuel for marine applications (not complete)
	Lloyd's Register: Class notation and descriptive note for vessels complying with the low flashpoint fuel requirements, e.g. LFPF(GF, ML), or with particular aspects 'ready', e.g. GR(ML, A)	
	Appendix LR1 – requirements for Ships Using Methyl Alcohol (Methanol) or Ethyl Alcohol	

Chapter 3:
Drivers for methanol

Introduction

Both the European Union and the International Maritime Organization have existing regulations that promote a reduction of CO_2 emissions from shipping. This is in addition to, pending or nascent regulations to further promote the use of clean fuels through market-based measures, fuel efficiency and emissions accounting requirements, and life cycle assessment of fuel.

This chapter summarises the state of play of the regulatory landscape along with the industry's connection with methanol as a marine fuel to offer insight into fuel acceptance and potential.

3.1

Regulations and lifecycle analysis

Regional regulations

The European Union has introduced both demand- and supply-side GHG emissions measures, through its Emissions Trading Scheme (ETS) and FuelEU Maritime Regulation.

From 2025, carbon dioxide (CO_2) emissions from ships ≥5000GT reported in 2024 under the EU's Monitoring, Reporting and Verification (MRV) system will also be included in the regional ETS. Vessels in scope of the ETS will need to buy EU Allowances (EUA) to cover half of their greenhouse gas (GHG) emissions to and from EU, Norwegian and Icelandic (EEA) ports and non EEA ports, as well as all emissions for intra-EEA voyages and while at berth at EEA ports. In 2025, 40% of the CO_2 emissions from voyages and at berth stays in 2024 will be subject to the ETS, ramping up to 100% in 2027. From 2026, the MRV will also require the reporting of CH_4 (Methane) and N_2O (Nitrous Oxide) emissions from ships, with EUAs to be paid on 100% of the CO_2 equivalent of those emissions, in addition to CO_2, within the ETS from 2027.

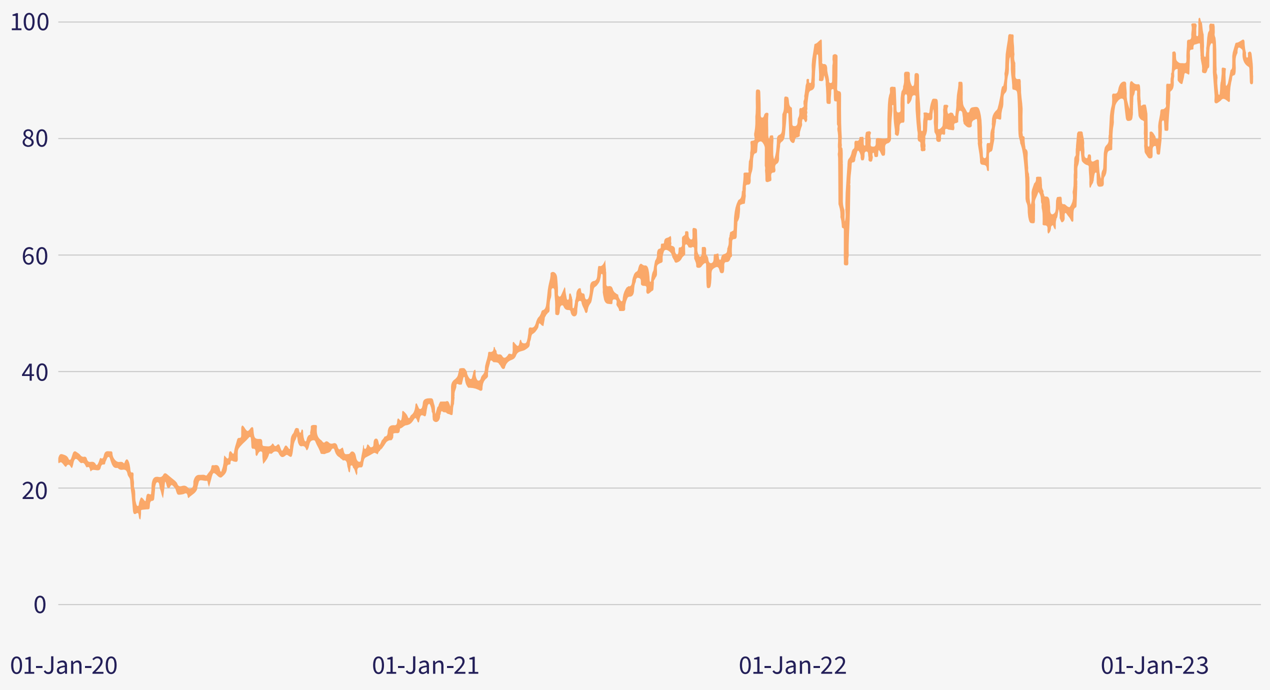
The other mechanism is FuelEU Maritime, which will come into effect in 2025. The regulation sets targets for reducing the yearly average GHG intensity of the energy used by a ship (or, crucially, by a fleet or pool of ships). The required GHG intensity reduction starts small, at 2% in 2025 (compared to a 2020 baseline), reaching 6% in 2030 and 14.5% in 2035, through to 80% by 2050. A penalty or reward is then calculated based on the extent of under- or over-performance against the vessel or fleet's target for the year, and the cost of low-carbon fuel that would have been needed to meet the target. While methanol emits carbon dioxide when combusted the carbon dioxide in green methanol is accounted for on a fuel life cycle assessment basis, where green and blue methanol will have emission benefits.

In addition to the FuelEU and EU ETS requirements, there are further regulatory texts under development within the European Union that will create the structure for renewable fuels to be produced and provide access to onshore power.

FuelEU, EU-ETS, and EU MRV are all part of the EU's regional Fit for 55 package of regulations, which are likely to rapidly drive decarbonisation at a regional level. Additional emissions trading mechanisms are under consideration in other regions including China, USA, and the UK.

If developed these additional regional mechanisms, combined with the EU's Fit for 55 package will cover much of the major global trading blocs. However, it is unlikely that each regional scheme will be the same leading to a fragmented global approach to decarbonisation, within the maritime sector.

European carbon price



Source: https://ember-climate.org/data/data-tools/carbon-price-viewer

International regulations

IMO regulations, relating to controlling CO_2 emissions at a global scale, are in force and have so far focused on fuel efficiency. In 2018, following the 2015 Paris Climate Agreement, the IMO agreed an initial GHG strategy to outline a pathway to reduce shipping emissions, focusing on CO_2 emission reduction from ships. This was in order to align with keeping global warming to within 1.5 degrees Celsius of pre-industrial global temperatures. The initial strategy led to the development of short-term measures including the Energy Efficiency Existing Ship Index (EEXI), the enhanced Ship Energy Efficiency Management Plan (SEEMP), and the Carbon Intensity Indicator (CII).

The IMO's Marine Environment Protection Committee (MEPC 80) has recently adopted a revised strengthened strategy which aims to achieve net-zero CO_2 emissions by or around, i.e., close to, 2050. There are some indicative checkpoints along the way – a reduction in carbon intensity of 20% striving for 30% by 2030, and 70% striving for 80% by 2040, compared to 2008 levels. There is also a target for low or zero carbon fuels uptake of at least 5%, striving for 10%, by 2030.

However, there are still some elements that need to be resolved over the coming 2–3 years – such as what the mid-term measures to reduce carbon emissions from shipping will be – they will have an economic and a technical element but the details on those are still to be negotiated and finalised. The IMO have adopted the fuel life-cycle analysis guidelines (LCA Guidelines) which will support the mid-term measures, in whichever form they are agreed.

There is still work to do – many are concerned that the 2023 GHG strategy is still not aligned with the 1.5 degrees Celsius goal from the Paris Climate Agreement. In 2028 a further revision of the strategy is timetabled which could then fully align it with that goal.

Lifecycle analysis

Within international discussions are the considerations of a lifecycle analysis of fuels. Methanol is a hydrocarbon, and therefore produces CO_2 when combusted. For green methanol to be part of the future of shipping, the methodology for assessing emissions from ships has to be calculated on a well-to-wake rather than tank-to-wake basis.

In a well-to-wake calculation, the GHG intensity of the fuel feedstock (including CO_2 for methanol), production process and associated transport – the so-called "fuel pathway" – are all accounted for. Tank-to-wake emissions evaluate the intensity of CO_2, CH_4, and N_2O emitted onboard a ship related to the fuel use and all relevant fugitive emissions.

The IMO has adopted the guidelines on the life-cycle analysis of marine fuels (LCA Guidelines) at MEPC 80. The well-to-wake and tank-to-wake emissions factors attributed to each fuel pathway and energy converter in the guidelines are expected to be used in future IMO legislation for the reduction of GHG emissions in shipping.

Lifecycle analysis guidelines and how they are applied by regulators determine how each specific fuel is treated under any market-based measure, and therefore have a crucial influence on shipowner investment decisions. Biofuels could be required to have certification of being a sustainable fuel from a recognised international standard such as ISSC or RSB.

3.2

Ship operator demand and interest

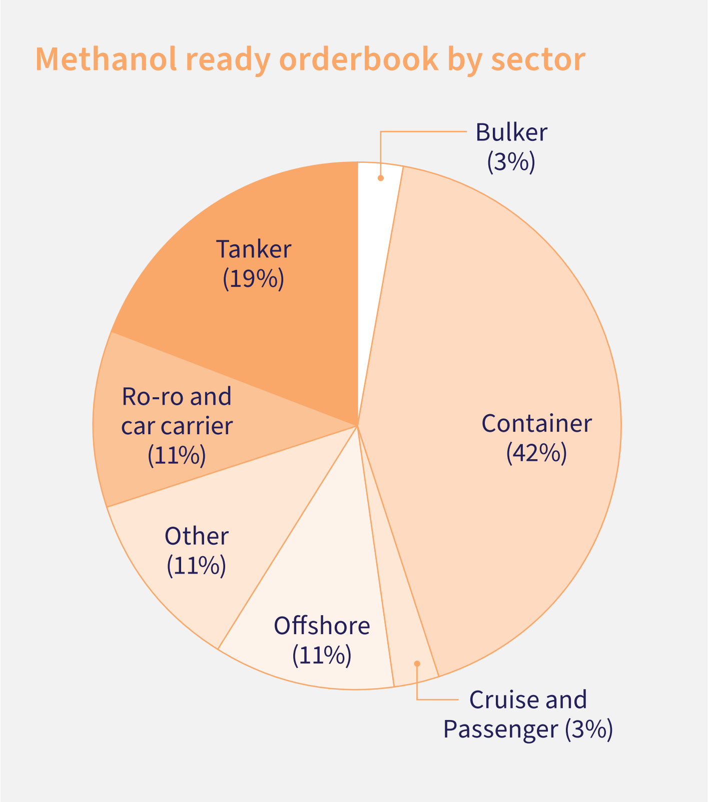
There is significant evidence of heightened interest in methanol-fuelled vessels. Clarksons reports (June 2023) that there are 29 methanol-fuel-capable vessels in operation and 112 on order, along with three methanol-ready vessels in operation and 128 on order. The new buildings are ready for delivery from 2023 to 2028 and consist of a growing range of vessels, with new orders being announced regularly.

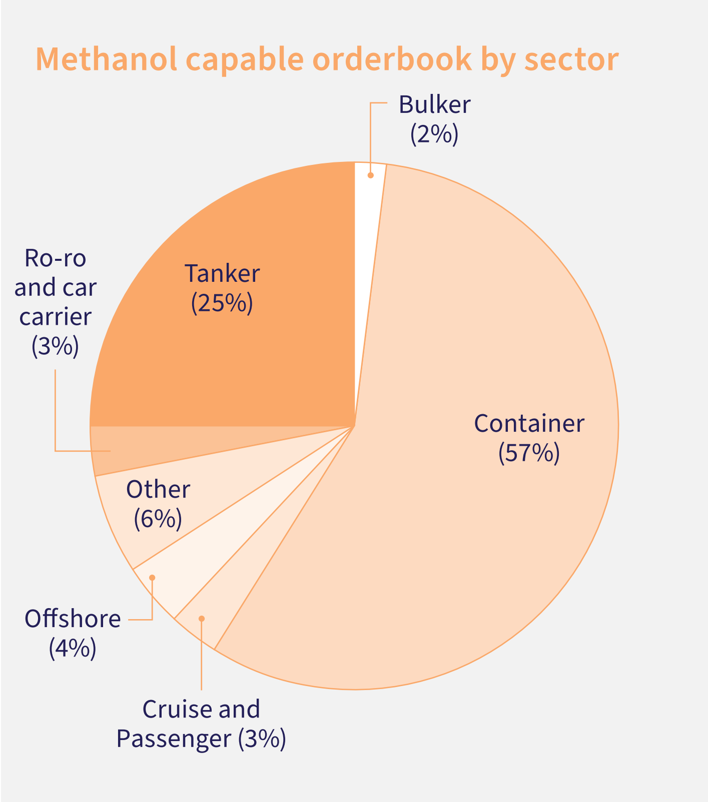
In March 2023, MAN stated it is in talks for up to 120 new methanol engine orders, with 80 signed contracts, adding that the methanol dual fuel two-stroke engine orders this year are greater than orders for similar LNG dual fuel engines.

The orderbook also lists 50 methanol-ready or multi-fuel ready orders. These vessels are being built with conventional fuel use upon delivery, but with designs that include a level of preparation for eventual conversion to methanol fuel. This includes four vessels on order in China, with the first three to be retrofitted for methanol once the newbuild methanol engine for the fourth vessel is completed.

Methanol fuelled newbuilding update

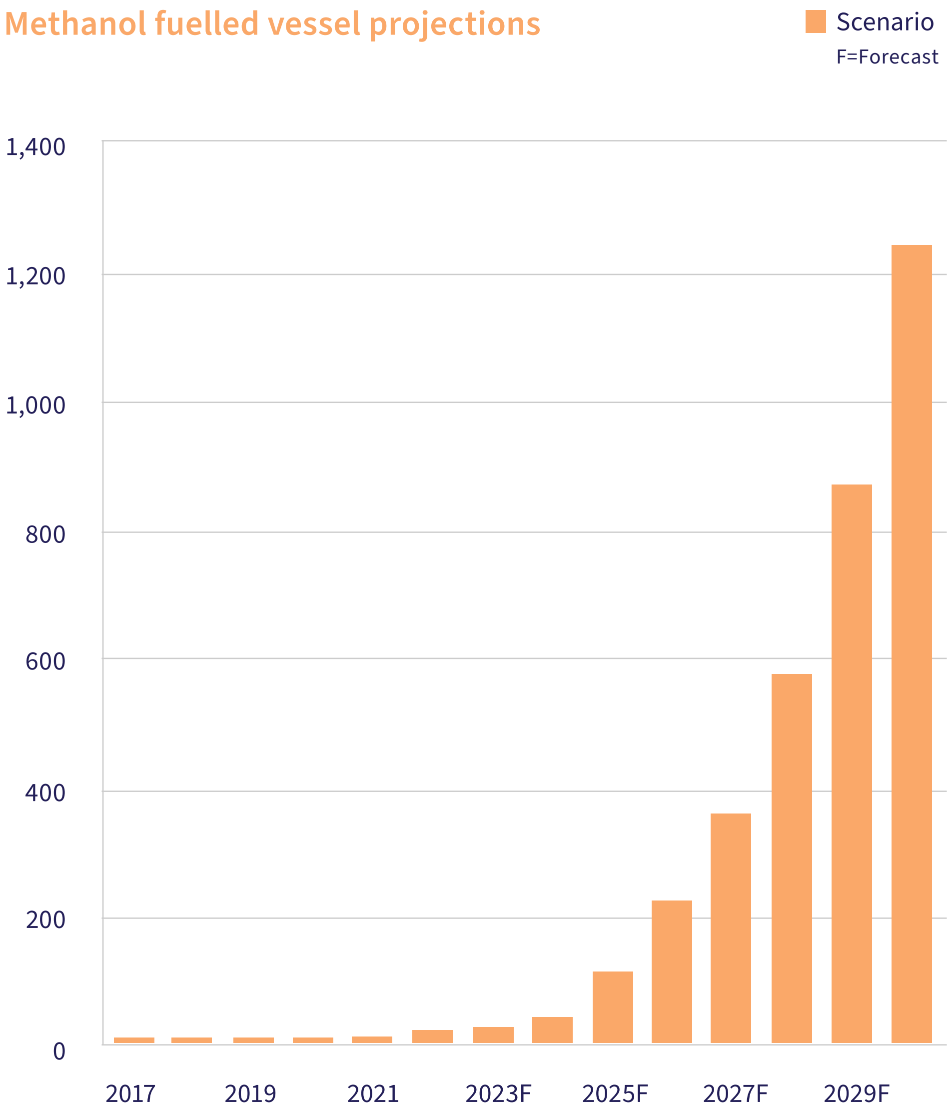
(Source: Clarksons, June 2023)





Clarksons forecasts suggest a significant climb in methanol capable and methanol ready orders. In 2022, methanol accounted for 3% of the orderbook (7% by GT). By 2030 this could be close to 20%, representing up to 1,200 vessels.

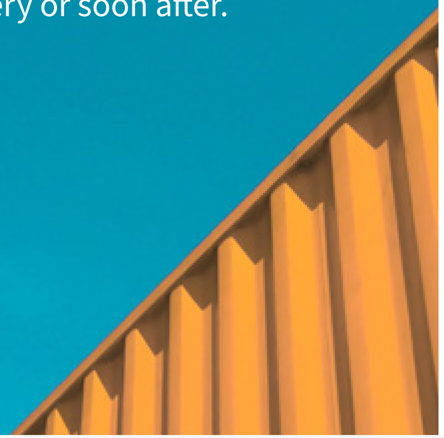
Methanol fuelled vessel projections



3.3

Techno-economic drivers

Making cost and economic estimations are difficult, but some factors are already available for owners and operators considering the two options of retrofitting vessels to become methanol/fuel oil dual-fuelled, or ordering newbuildings that are methanol dual-fuelled upon delivery or soon after.



Newbuilding value proposition

Building a methanol ready or capable vessel is a commercial decision where operational expenditure and revenue factors such as customer ability and willingness to invest in green supply chain assets, carbon pricing and green methanol fuel price, influence initial capital investment decisions. Capital expenditure decisions revolve around yard availability, engine and machinery overheads and related onboard fuel infrastructure decisions.

Owners are therefore hedging options by ordering vessels designed on flexibility using various stages of a readiness notation to balance capital investment now with any subsequent retrofit costs.

Industry indications point to a two-stroke methanol dual fuel engine having a 10% premium on now established dual fuel LNG engines, while four-stroke engines will be comparable.

Methanol ready

There is a certainty that regulations to reduce greenhouse gas emissions from shipping will be agreed at a regional and international level, but great uncertainty over how these regulations can be met.

Owners looking at newbuilding orders today know that they need vessels that will be commercially attractive for decades to come, but do not know what decisions will be the correct one. One solution today is to design vessels under a fuel ready notation where certain capital expenditure can be made during newbuilding to prepare a vessel for a fuel should conditions make that fuel option viable.

Owners and shipyards can opt for a staged approach from simple preparations, for more than one fuel type, or make more substantial investments in the newbuilding to reduce the time and costs of a subsequent retrofit.

Retrofit value proposition

While newbuilding orders may be built to designs where retrofitting is easier and more cost efficient by considering eventual methanol fuel use, most younger tonnage in service has not been built with a retrofit installation in mind.

Such vessels will require investment in engine overhaul, often a complete engine strip down and rebuild, supplementary fuel systems and safety measures and the adaption of one or more existing fuels tanks to be able to hold methanol fuel.

Costs include engine rebuild, piping, fuel system, tank coating, as well as design, planning and drydock costs. Indications suggest that engine and fuel system costs, which will be most of the overheads, could be in the range of 10% to 25% of a vessel's value.

Owners of vessels with an interest in retrofitting will also need to evaluate the NOx emissions implications of such retrofitting conversions or the installation of new engines into vessels.

New build and retrofit economic modelling

Modelling of capital expenditure and operational expenditure throughout a life cycle of a vessel is difficult. It's impossible to generalise given how vessel size, purpose and operational profile will play a role in any calculations, as will predicted methanol prices, and carbon price.

From a retrofit perspective the costs of rebuilding an engine need to be carefully evaluated given not all engines will have a test engine equivalent to ensure it meets emissions testing requirements under IMO regulations.

Methanol pricing will totally depend on green electricity, hydrogen and biomass feedstock prices. If low enough, it could reduce the difference compared with fuel oils, gas oils and diesel, but a carbon price or carbon credit would further increase competitiveness.

One recent TCO assessment (Danish Technology University 2022) on total cost of ownership suggested a 15,000 TEU containership with 50MW engine power would have the following:

CO_2 tax		€25		€300	
Year		2020	2030	2020	2030
Biomethanol	TCO $m per year	99	94	117	97
E-methanol (with CCU)	TCO $m per year	119	93	153	121
VLSFO (very low sulphur fuel oil)	TCO $m per year	43	40	95	93

3.4

Total cost of ownership case study

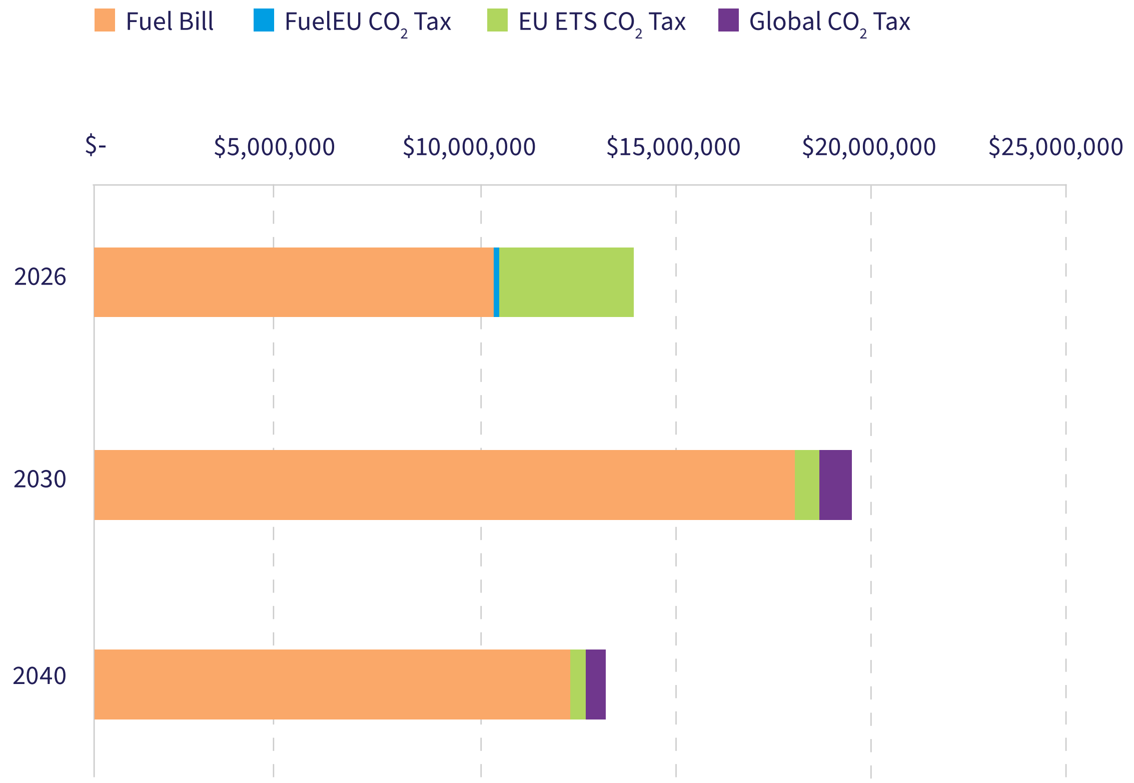
Shipowners and operators need to consider a number of different scenarios and variables when determining if a vessel should be built or retrofitted to be capable of using methanol as an alternative fuel. The example below is a snapshot of just some of the economic considerations.

The vessel is a 10-year-old 2,500 TEU feeder container vessel operating in North Europe with a current fuel of low sulphur fuel oil or diesel and consuming 33mt per day. Annual hire days when the vessel is on charter are taken at an average of 325 days and there is an assumed life span of 25 years. For the sake of this study, the vessel spends 100% of its trading life within the European ETS, with associated costs set to grow.

The total cost assumptions (not including conversion costs) are for 2026, 2030 and 2040, and clearly show that production costs of green methanol, along with the application of either global or regional carbon pricing mechanisms, heavily influence the results.

Please note these tables come with uncertain assumptions on costs and other industry developments and are for illustrative purposes only.

Operational fuel costs related to a switch to methanol for a 2,500 TEU containership on intra-European trade



(See Annex at end of this report for more detail on assumptions)

4.1

Chapter 4: Methanol production and supply

Introduction

Successful deployment of methanol as a marine fuel relies on renewable production, from electrolysis and/or bioresources. More than 80 production projects are being tracked by the Methanol Institute with estimated production of more than 8m tons renewable methanol per year by 2027.

Much of the current methanol demand is met through the production from synthetic gases using coal or natural gas as a feedstock (brown and grey methanol). Depending on the pending decisions on CO_2 life cycle accounting at an international level, the successful use of methanol as a marine fuel relies on the production of blue and green methanol (see definitions in annex 5) in sufficient volumes and cost.

This chapter gives an overview of production methods and the expected future supply of blue and green methanol in the coming years.

While standard methanol, biomethanol and e-methanol (brown, grey, blue and green) are chemically identical, their production pathways, and the verification of these pathways, will be the determining factor in acceptance as a net-zero marine fuel.

Additionally, shipping will compete with road transport and the chemical industry for the green methanol as pressure mounts for all sectors to decarbonise. From this perspective, green and blue methanol price, the price of carbon and fuel availability will be the determining factors impacting fuel supply.

The life cycle emissions from current methanol production are 0.3 gigatons CO_2 per annum. Over the last decade, production has nearly doubled – reaching 98m tons (there has been a large increase in China where production is from coal) in 2019. It is predicted to rise to 120m tons in 2025, before increasing to 500m tons per annum by 2050. 500m tons of methanol will therefore produce 1.5 gigatons of CO_2 if production pathways do not move away from fossil fuels. Renewable methanol production in 2021 was only 0.2m tons.

This chapter gives an overview of production methods and the expected future supply of blue and green methanol in the coming years.

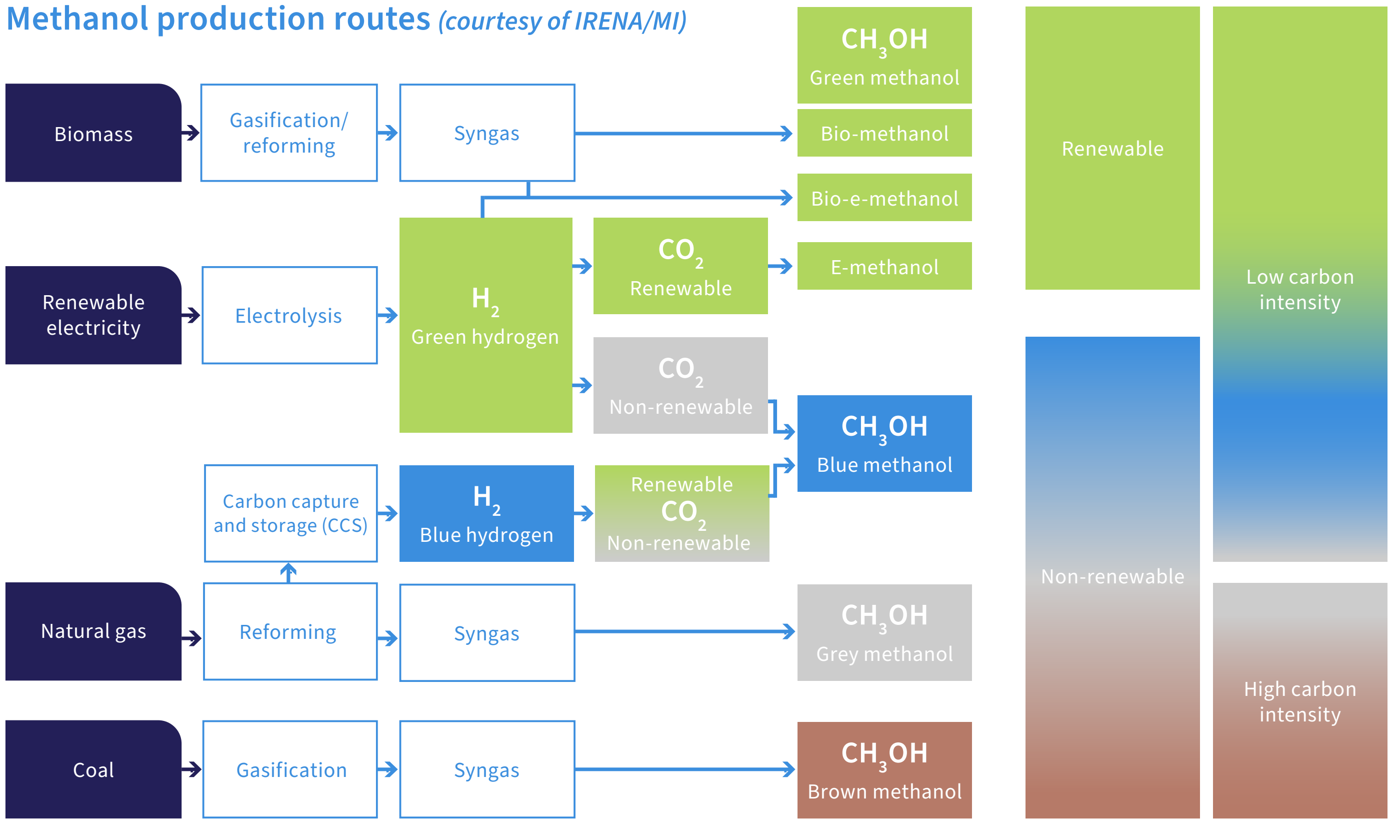
4.2

Production pathways

Current industrial methanol production

On an industrial scale, methanol is predominantly produced today from natural gas by reforming the gas with steam and then converting and distilling the resulting synthesised gas mixture to create pure methanol. Current total methanol production, of all colours, is over 110 million tons a year, with the majority being used in chemical and petroleum industrial applications, as well as the production of consumer products. More on methanol production routes can be found on the Methanol Institute website.

Methanol production routes *(courtesy of IRENA/MI)*



Biomethanol production

Biomethanol (green methanol) is produced by using biomass feedstocks (Forestry and agriculture waste and by-products, such as black liquor from P&P (Pulp & Paper) industry, biogas from landfill, sewage and municipal solid waste). With low production volumes the cost of production can only be estimated.

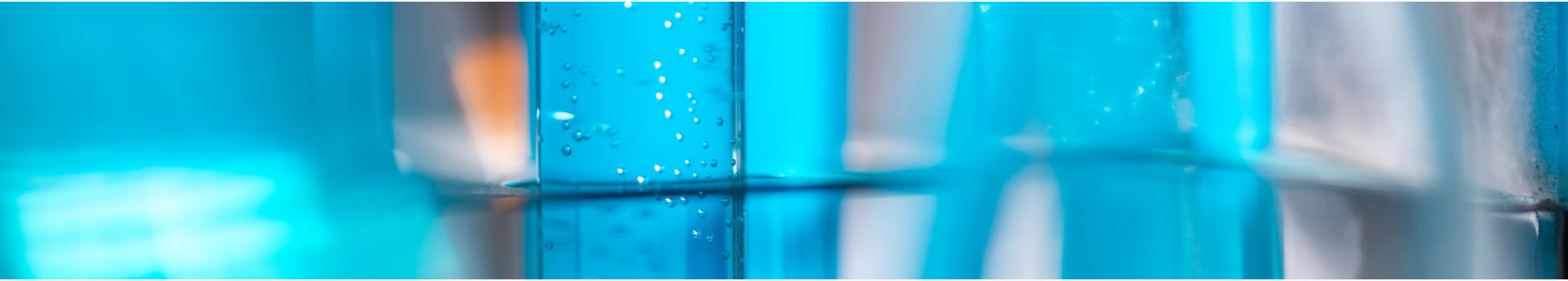
The cost of biofeedstock (biomass feedstock varies from 0 to $17 per gigajoule) investment costs and the efficiency of the conversion will play a role. An IRENA estimate in 2021 was for biomethanol to cost between $320 and $770 per ton, but process improvements could see this drop to a range of $220 to $560 per ton if feedstock is under $6 per gigajoule (GJ). Production of biomethanol when close to waste sources such as pulp and paper and Municipal Solid Waste (MSW) will help streamline production and improve overall economies of scale. Eventual bunker prices of biomethanol will depend on feedstock prices, the cost of hydrogen, and the cost of electricity. Additional capital costs for producers such as electrolysis and plant investments need to be considered as well as subsequent transportation costs.

E-methanol production

E-methanol (green or blue methanol) is obtained by combining captured CO_2 with hydrogen from renewable electricity. The CO_2 sources could be from industrial carbon capture including BECCS (bioenergy with carbon capture) and DAC (direct air capture).

The hydrogen is produced through one of two ways, whether by using renewable electricity to electrolyse water into oxygen and hydrogen (green hydrogen) or through the reformation of natural gas, or coal, providing the CO_2 emissions during this process are captured (blue hydrogen).

E-methanol costs will depend heavily on green electricity costs, hydrogen costs, infrastructure and capital investments. IRENA production cost estimates for e-methanol today are between $800 and $1600 assuming CO_2 is from BECCS, with a cost of $10 to $50 per ton CO_2 ($1200 to $2400 per ton methanol if the CO_2 comes from DAC).



Green methanol production projects by country

Projects are in various stages of operation

Source: The Methanol Institute

The growing number of green methanol production projects around the globe can be seen on the Methanol Institute dashboard. The Institute is tracking 90 projects that are projected to produce almost 9m tons of methanol annually when online (by 2027). This production will not be dedicated to shipping use, but some projects are.

A detailed list of methanol production plants under development can be found in the annex of this report, data courtesy of the methanol institute.

4.3

Fuel price

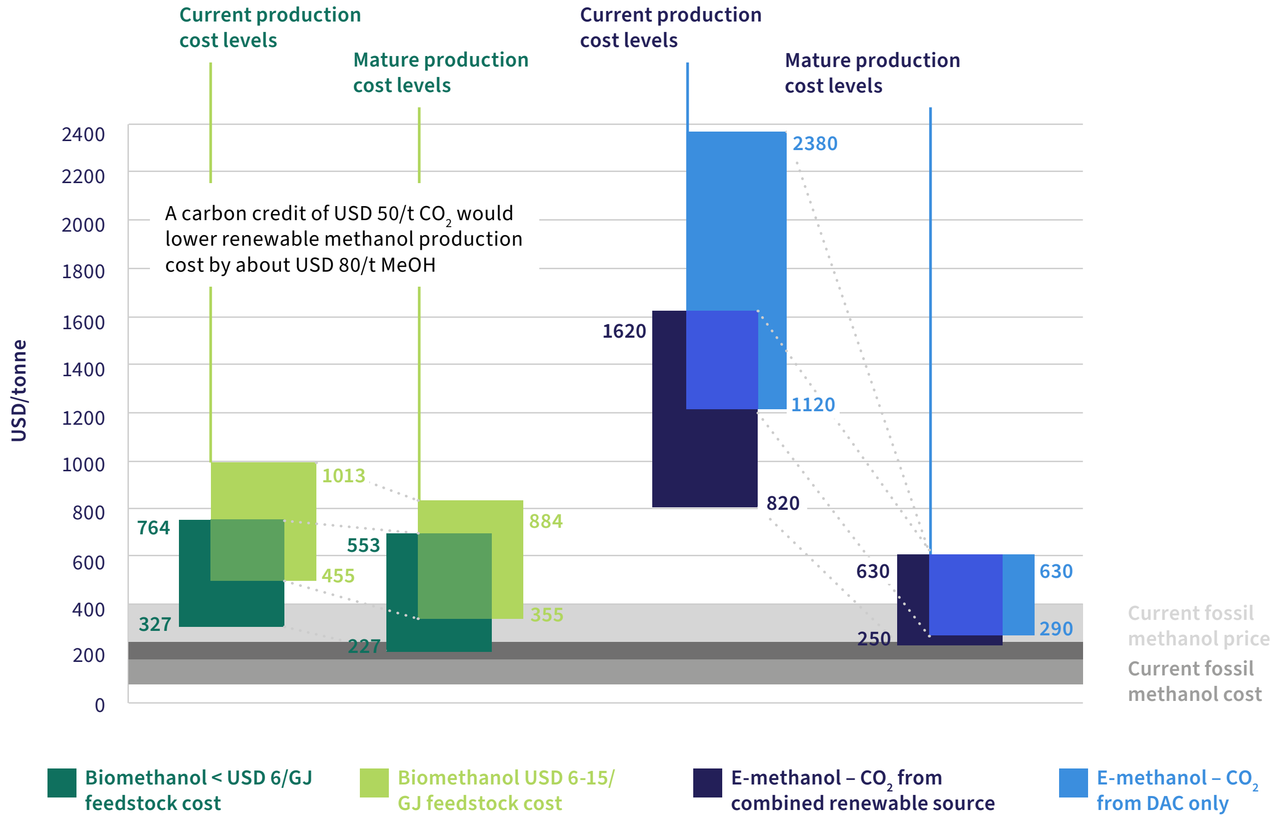
Grey methanol prices vary regionally (Asia, USA and Europe) with spot market average prices and forward contracts (see table). Prices range from $327 to $366 per ton on the spot markets for February 2023. These prices are trading prices, and it is expected that green and blue methanol prices will be scarcer and more expensive. Additionally, bunkering infrastructure costs will create added expenses when cleaning methanol bunkers in ports and terminals. Estimates have pointed to green methanol being supplied initially at around $1,000 per ton.

Potential methanol price trends

While very low sulphur fuel oil is $600 a ton, marine gas oil is at approximately $876 per ton while fuel oil (IFO380) is at $465 per ton. When the different energy density between the fuels is considered, (for methanol x2.4) then the price of methanol as a marine fuel remains unfavourable without a price mechanism to encourage take up.

Green methanol production costs remain uncertain. While the number of production plants under development grows, very few are currently in operation and producing significant volumes of methanol. The adjacent table highlights the range of projections on production costs alone, making economic modelling for producers challenging. With grey and brown methanol users likely to also seek blue and green alternatives in the future, the market pressures on cost and availability will remain uncertain until some of these new renewable methanol projects are online.

Current and future production costs of bio- and e-methanol



Notes: MeOH = methanol costs. Costs do not incorporate any carbon credit that might be available. Current fossil methanol cost and price are from coal and natural gas feedback in 2020. Exchange rate used in this figure is USD 1 = EUR 0.9

Source: IRENA (&MI) Innovation Outlook; Renewable Methanol (2021)

Global methanol pricing comparison

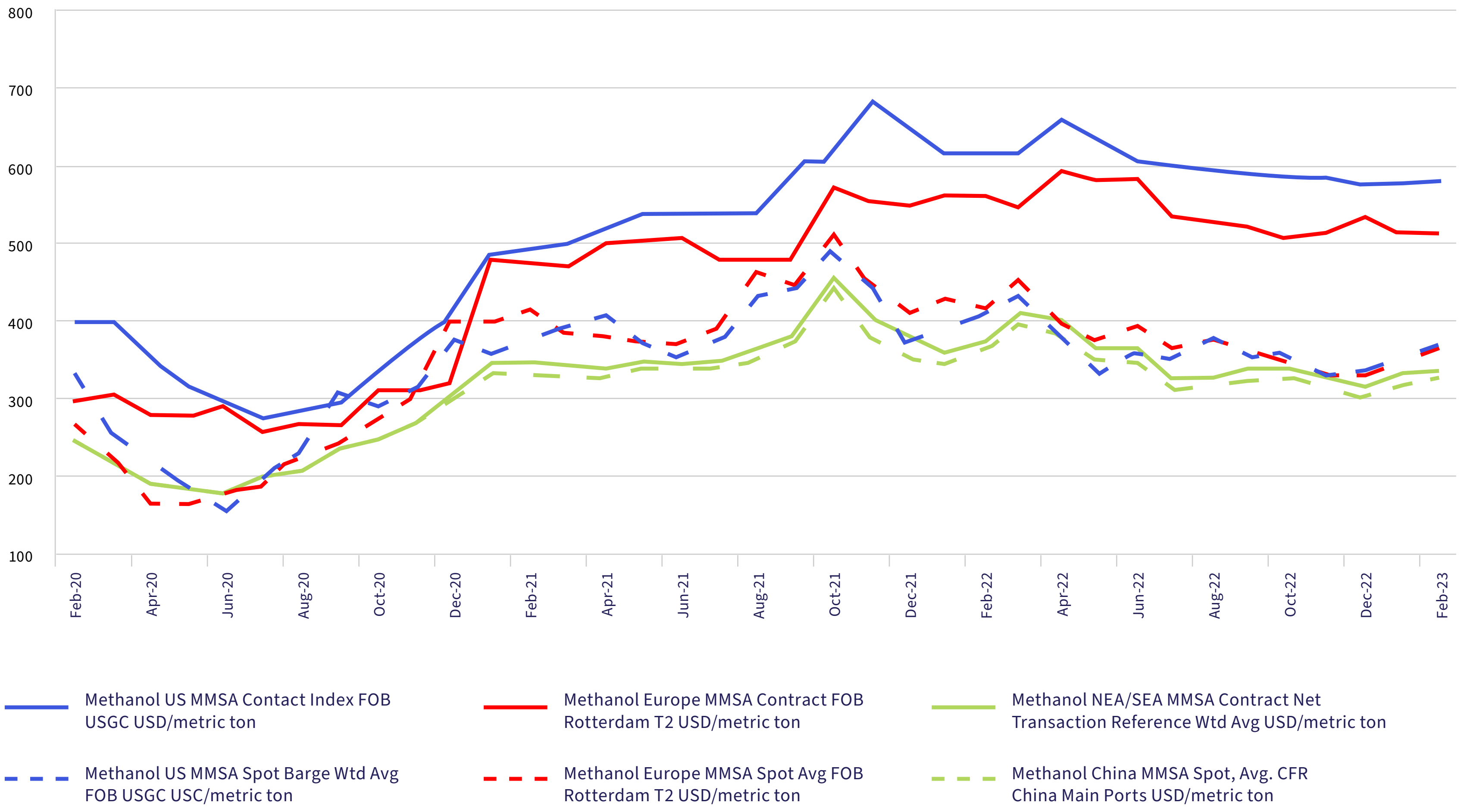


Table data extracted from: https://www.methanol.org/methanol-price-supply-demand

4.4

Volume projections

(from Global Maritime Forum 2021)

With Maersk Line ordering a series of methanol dual-fuelled vessels, the organisation published methanol demand projections for its own needs in 2021. The organisation estimated that 300,000 tons of green methanol would need to be supplied to the company by 2024. If the whole Maersk fleet were fuelled by methanol, it would need approximately 2m tons of green methanol.

Annual production of green methanol (in k tons)

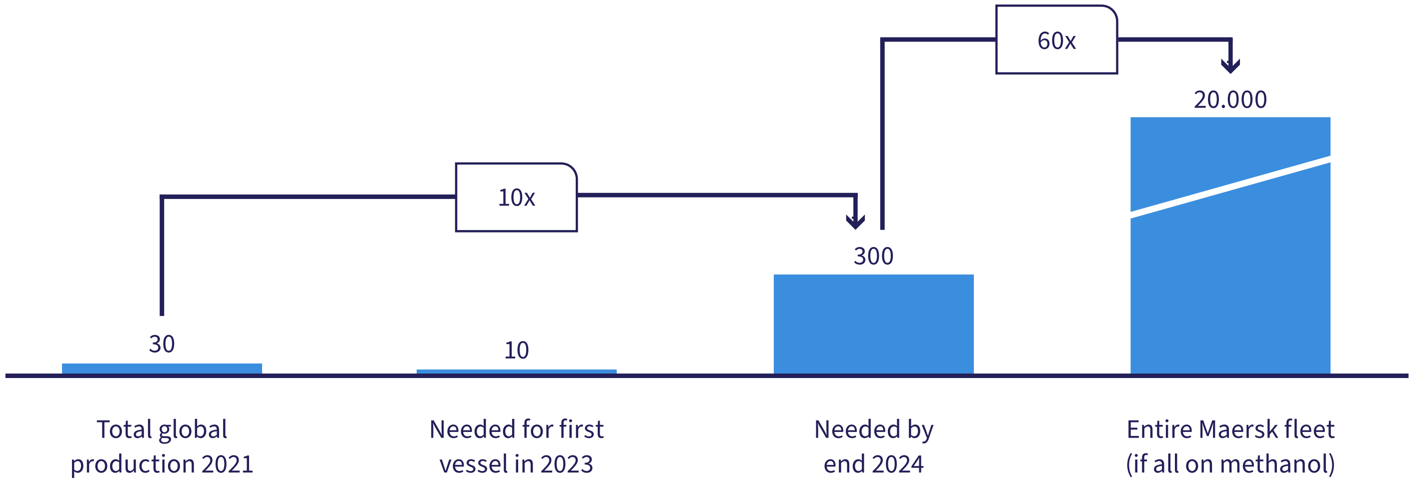
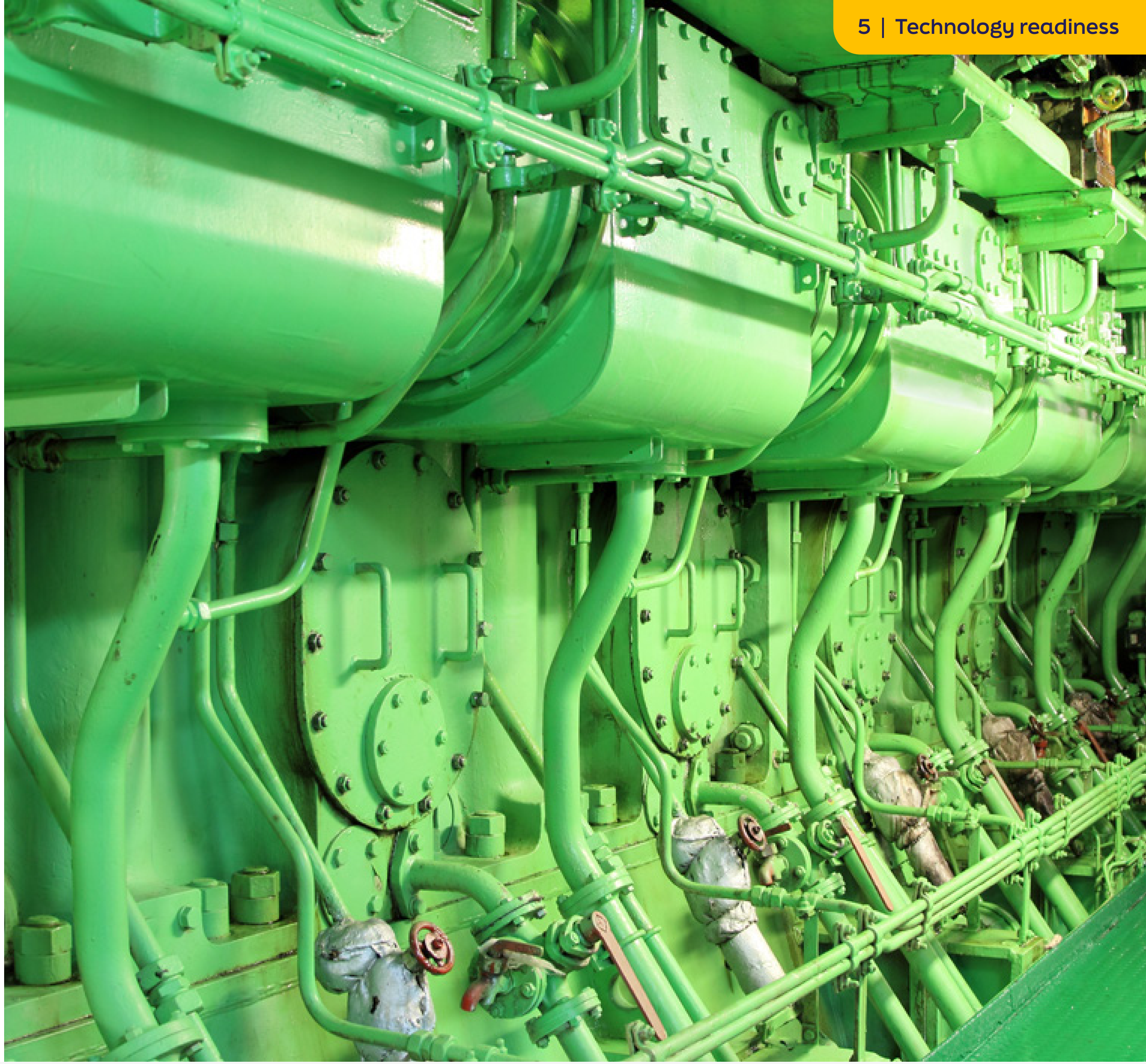


Exhibit 4: Maersk projection for methanol need
Source: Maersk (2021)

Chapter 5: Technology readiness



Introduction

Because methanol is a liquid at ambient temperature and pressure, the process of supplying it as a fuel into marine engines is similar to conventional fuels, but with the unique safety issues to observe, as mentioned in Chapter 2.

An engine will need approximately 2.4 times the amount of methanol as diesel for the same fuel energy density, an indication of the increased volume of methanol storage needed to achieve the same amount of energy when making a comparison to existing propulsion.

Engine makers are in advanced stages of developing a variety of engine options for shipping, including conversion kits for owners who are considering this pathway to compliance and lower emissions. Additionally, technology companies are developing onboard systems to be able to generate hydrogen from methanol for use in PEM (Proton Exchange Membrane) fuel cells.

5.1

Marine engines and conversions

All the major engine makers now have designs for two-stroke and four-stroke internal combustion engines capable of using methanol as a fuel. All are dual fuel engines, capable of using marine diesel, marine gas oil or fuel oils as a fuel. All these engines require a pilot fuel to be injected into the engine cylinders with the methanol to initiate combustion.

MAN ES, Wärtsilä and WinGD represent the majority of two-stroke and medium-speed four-stroke engine models that can be found onboard most commercial tonnage. All three have roadmaps for the development of their engine portfolios to meet the expected demand for future fuels.

Two-stroke engines

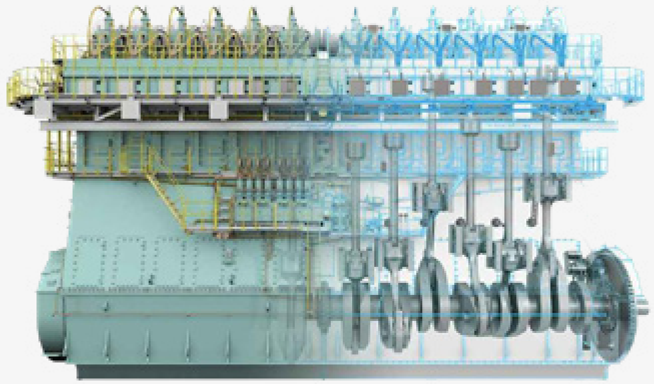
MAN ES has won several orders for its MAN B&W ME-LGIM dual-fuel methanol engine, notably from containership owners who have made the strategic decision to move towards methanol fuels. The company has these engines on 20 vessels that are currently operational, including several methanol carriers that can use their cargo as fuel, but has an orderbook of 90 (as of May 2023) newbuildings with one engine apiece. These are largely with container liner operators such as Maersk Line, Hyundai, CMA CGM and Cosco Shipping. The vessels are built under license by engine makers in South Korea, Japan, and China.

WinGD, the Swiss-based engine designer has announced some of its first two-stroke methanol dual-fuelled orders in China. Notably, an order for a 90-bore engine on four container ships will see the company work with the yard and a local engine maker to build the first three engines with a standard dual fuel engine and have the methanol fuelled design ready for direct build into the fourth of the series. This allows WinGD to simultaneously build a retrofit process which it will then use on the first three in this newbuild series, and then offer to the market for ship operators considering methanol conversions.

MAN ES is also developing a retrofit programme for its two-stroke MAN B&W ME-C engines to dual-fuel operation on methanol. The company says it designs its ME-C engines to be fully dual-fuel ready, with potential conversion not just for methanol but for an array of other alternative fuels.

It is worth noting that methanol fuelled two-stroke dual-fuel engines require a pilot fuel for combustion, representing between 5% and 10% of the fuel mix, depending on engine type and load. The pilot fuel would be a marine diesel or gasoil.

MAN ES
(ME-LGIM in service)



WIN GD (in development)

The LR-class Stena Germanica was the first conversion project demonstrating methanol fuel capabilities. Initially one of the four Wärtsilä ZS40 engines of the 2001-built vessel were converted to be dual-fuelled, capable of running off methanol or marine diesel or gasoil. Shortly after the remaining three engines were also converted to be methanol dual-fuelled. The conversion project was EU funded.

According to the Methanol Institute (and FCBI) conversion costs amounted to €13m with overall project costs amounting to €22m, which included a methanol storage tank ashore, a bunker barge adaption and pioneering project work, including safety assessments and adaption of rules and regulations. Estimates suggest subsequent retrofit costs could be 30% to 40% lower.

Over the eight years since the conversion, Lloyd's Register and the vessel operator have gained valuable tangible experience for in-service maintenance and performance monitoring of a dual-fuelled vessel. Stena line has now contracted Wärtsilä to convert an undisclosed number of its other ferries to be dual-fuelled (June 2023).

Four-stroke engines

Wärtsilä now has a modified four-stroke 32-bore design, as does Hyundai, with the HiMSEN methanol H32DF-LM. Hyundai claims orders for 74 sets of its four-stroke HiMSEN methanol engines as of the end of March 2023. Hyundai's engines use the diesel cycle and have electronically controlled, common rail, fuel injection. The first of the HiMSEN engines will be installed onto two Maersk methanol dual-fuelled vessels: A six-cylinder version on a 2,100 TEU vessel and a nine-cylinder version on a larger 16,200 TEU vessel.

HiMSEN engines will require a mix of about 10% pilot fuel (MDO/MGO) when fuelled with methanol. The engines can also use fuel oils.

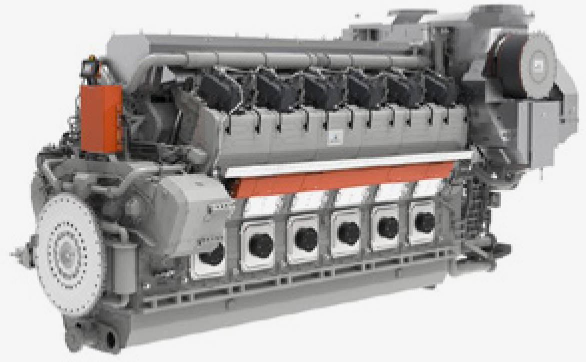
For the four-stroke market MAN ES is still working on methanol injection technologies for both newbuild and retrofitting, with the retrofit option coming first. This is being tested out in one order where a 48/60 (480 mm bore with 600 mm stroke) four-stroke engine will be converted to a 510 mm bore engine, thus becoming one of the company's latest engine designs, a 51/60 DF engine.

The 51/60 dual-fuel engine size is likely to be the first four-stroke design that MAN ES will offer for newbuildings. It believes the focus for four-stroke conversions will be for the passenger and ROPAX (roll-on/roll-off passenger) markets, with its first retrofits being engines in two cruise vessels under a pilot project in 2025 and a RO-RO (roll-on/roll-off) vessel in 2026.

These engines also require a diesel or fuel oil pilot fuel injection when using methanol fuel. MAN ES says its calculations suggest that the pilot fuel will be between 1% and 3% of the fuel mix, depending on engine load and the inclusion of optimised methanol-diesel share with Port Fuel Injection (PFI) technology.

The Hyundai HiMSEN engine could be about 10% at optimal engine loads. MAN ES is investigating whether methanol fuelled engines could have a spark plug design to avoid using any pilot fuel.

In addition to MAN ES, Hyundai HiMSEN, WinGD and Wärtsilä, there are other engine markers developing solutions capable of being fuelled by methanol. These include Anglo Belgium Corporation (ABC), Caterpillar, China State Shipbuilding Corporation (with Hudong Heavy Industries), Rolls-Royce mtu Marine Solutions, ScandiNAOOS/Nordhaven Power Solutions.



Wärtsilä W32

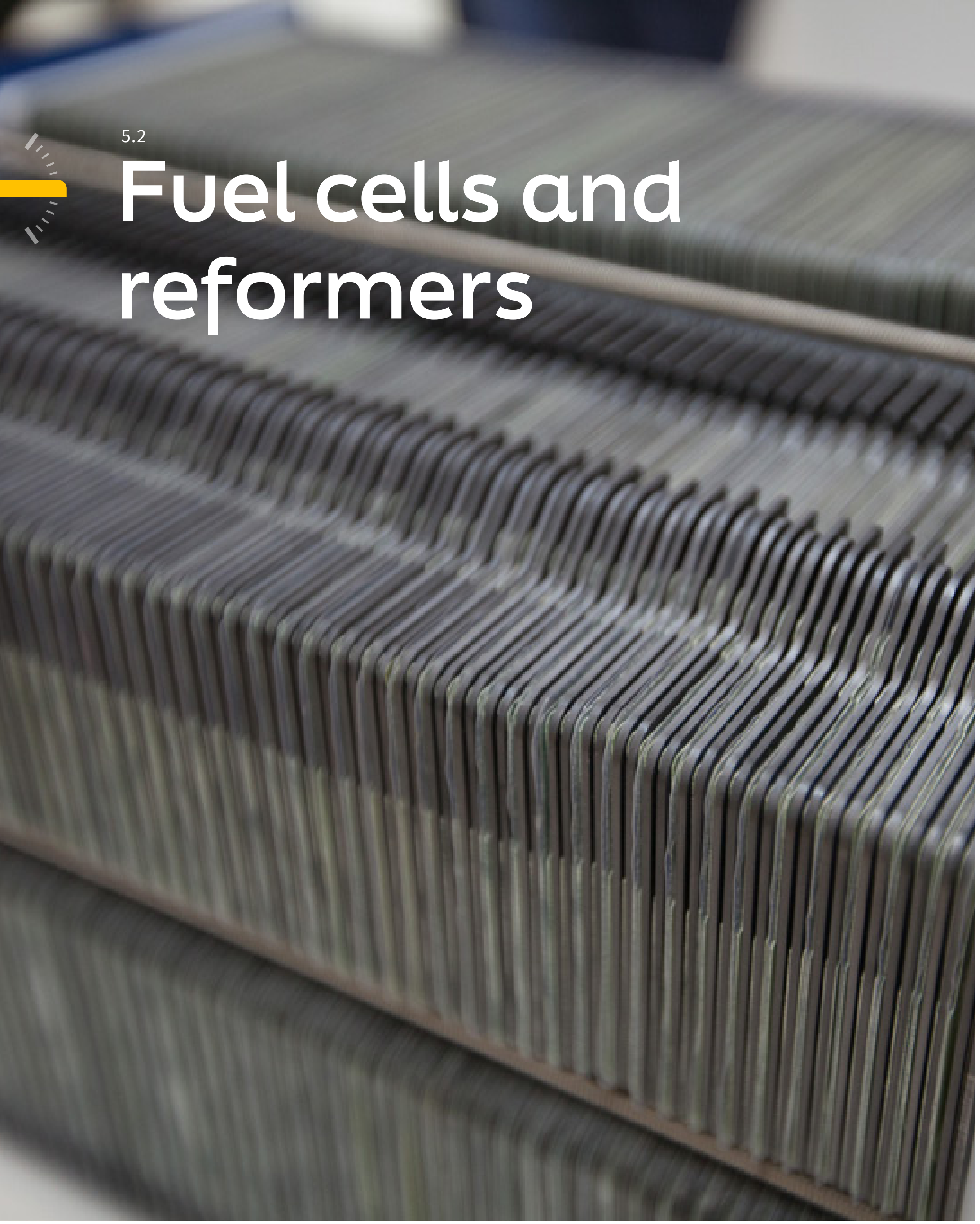
Hyundai HiMSEN

Retrofit challenges and NOx emissions

Retrofitting any vessel to adapt to a new fuel will require close collaboration with a repair yard and getting the competence to plan and perform the work. As well as early planning to prepare the vessel, safety systems and engines, plans will also have to be drawn up for fuel tank sizes.

Requirements for fuel tanks may cause fuel tank space to be reduced. It is important for vessel operators to understand the future operational profile of the vessel, the ensuing fuel demands that profile creates and the tank volumes that will be needed. Operators also need to ensure that emissions profiles are understood, including CII calculations and NOx emissions. A major engine conversion (replacement) may result in the vessel being required to meet NOx tier III levels, thus requiring additional NOx reduction technologies. Any main engine conversion will require new NOx emission certification.

Most engine makers also produce NOx reduction technologies such as selective catalytic reduction systems or exhaust gas recirculation. Another technology involves the addition of water into the methanol to reduce NOx emissions.



5.2

Fuel cells and reformers

Fuel cells

Fuel cells are increasingly being seen as an option for some shipping sectors as they provide a reliable way to generate green electricity with high efficiency. Their use has been growing in smaller vessel segments such as coastal ferries, offshore vessels and some short sea and inland waterways craft. They are also being viewed positively as with fewer moving parts and less maintenance needs than internal combustion engines they are probably cheaper to operate with less human intervention, helping in the move towards greater automation.

Methanol can be instantly utilised by direct methanol fuel cells (DMFCs), a sub-category of the proton-exchange membrane fuel cells (PEMFCs). However, their efficiency and power density are significantly less compared to hydrogen-fuelled PEMFCs. The solution that is being developed is to efficiently convert methanol into hydrogen onboard the vessel, with CO_2 as a by-product, and feed the hydrogen into the fuel cell to generate electricity.

The use of fuel cell technology on ships has similar safety considerations as for marine gas engines, including ventilation requirements, double-wall piping, gas leak and fire detection. Further information regarding safety and functional requirements for fuel cells on board ships can be found in LR's Rules and Regulation for the Classification of Ships, Pt 5, Ch 26 Fuel Cell Power Installations.

However, fuel cell stacks will also have a specific lifespan, needing replacement after a certain number of hours. Other maintenance work to be expected may include coolant replacement and the regular check of gas detection sensors, and replacement as necessary.

In operation, fuel cells will typically have slower ramp up times than engines. For example, in vessels requiring sudden and dramatic changes in propeller thrust, a fuel cell may be too slow to respond to the load demand. Therefore, fuel cells and marine batteries will be typically installed together, with the batteries to cover any peak loads, as long as the fuel cell increases its power output to meet the demand.

Further information regarding marine fuel cells, considerations during design phase and installation requirements can be found in LR's Guidance Notes on the Installation of Fuel Cells on Ships.

Onboard conversion/reformers: methanol to hydrogen

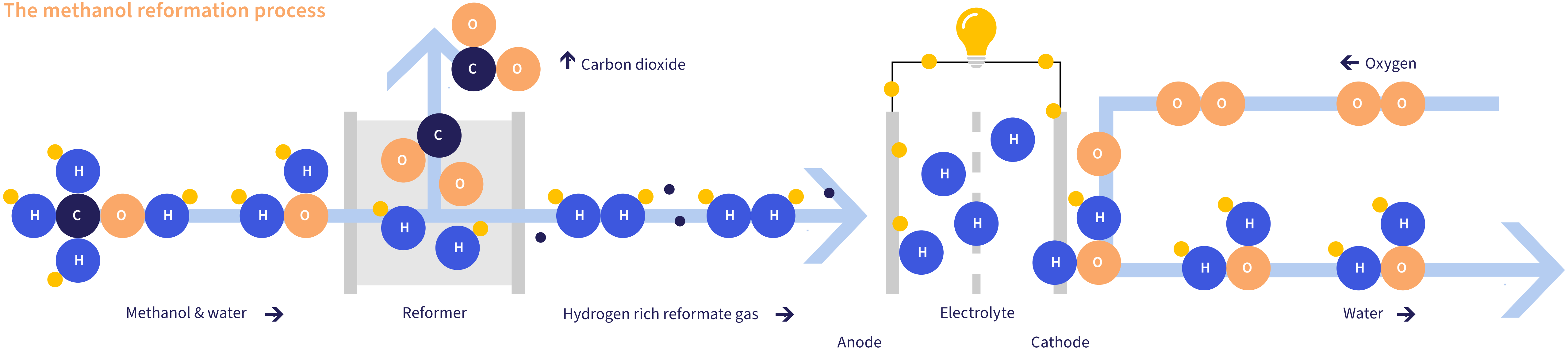
As mentioned, there is ongoing research into marinising the technology to convert methanol to hydrogen to allow the hydrogen to be used in PEM fuel cells. There are several key factors why this is being seen as a potential suitable pathway for some vessels.

The energy can be stored as a liquid – green methanol – and does not require specialised storage that could take up valuable space, such as would be required with LNG, ammonia or hydrogen. It also allows fuel cells to be used either as a direct power source or as auxiliary engines/generator sets.

Reformers require a power source but generate CO_2, carbon monoxide and hydrogen. The CO_2 would be emitted as exhaust or captured, and the hydrogen used in the fuel cell. Safety concerns will be over leaks of any of the three gases.

Companies such as e1 Marine and RIX Technologies are working on reformer technologies for shipping. Demonstration projects and first uses cases in smaller vessels such as tugs have been run.

The methanol reformation process



5.3

Fuel tanks and other fuel systems

Methanol is corrosive and cannot therefore be stored in regular (fuel oil, gasoil or diesel) fuel tanks onboard vessels. The tanks need to be stainless steel or carbon steel with a coating. The coating needs to be a proven coating such as those found inside cargo tanks of methanol carriers. These are suitable for methanol and methanol vapour in the ullage space as well as the required inerting system.

An inert gas system will need to be installed if not already planned for other purposes. Fuel tanks will require a cofferdam if built into the ship design and have provisions for venting, gas detection and safe access. Provisions for an overflow tank are also required. They can be located under the deck.

Other fuel related technologies required for methanol fuelled vessels include potential use of:

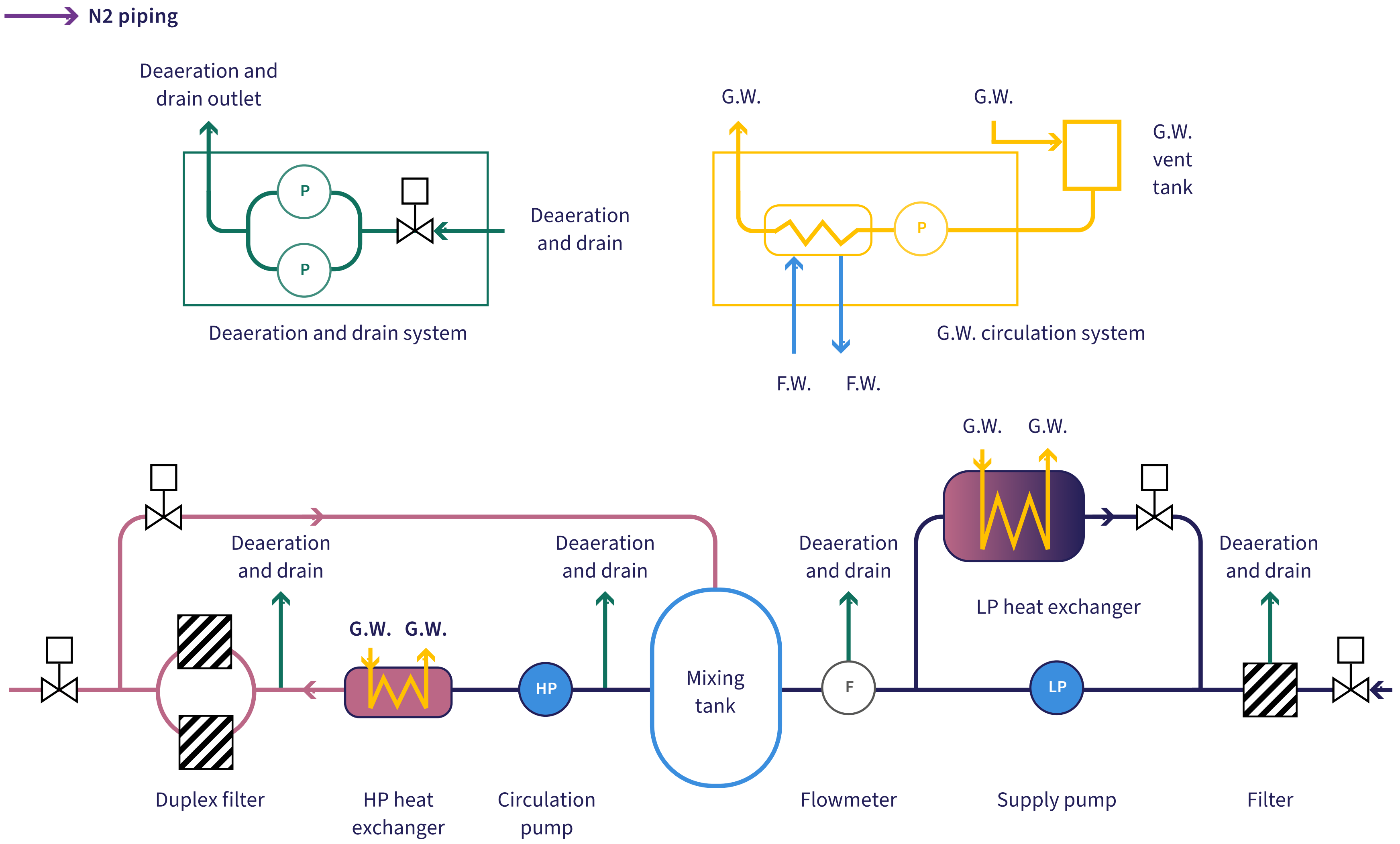
- Fuel Valve Train: for controlling methanol supply and for purging. Placed in hazardous area
- Methanol high pressure pump: sets pressures of up to 300 bar for high pressure fuel engines
- Possible nitrogen, or other inert gas, generation as leak protection
- Double wall piping at high pressure parts in engine room
- Air ventilation for methanol piping
- Methanol monitoring system and alarms

Liquid fuel supply options

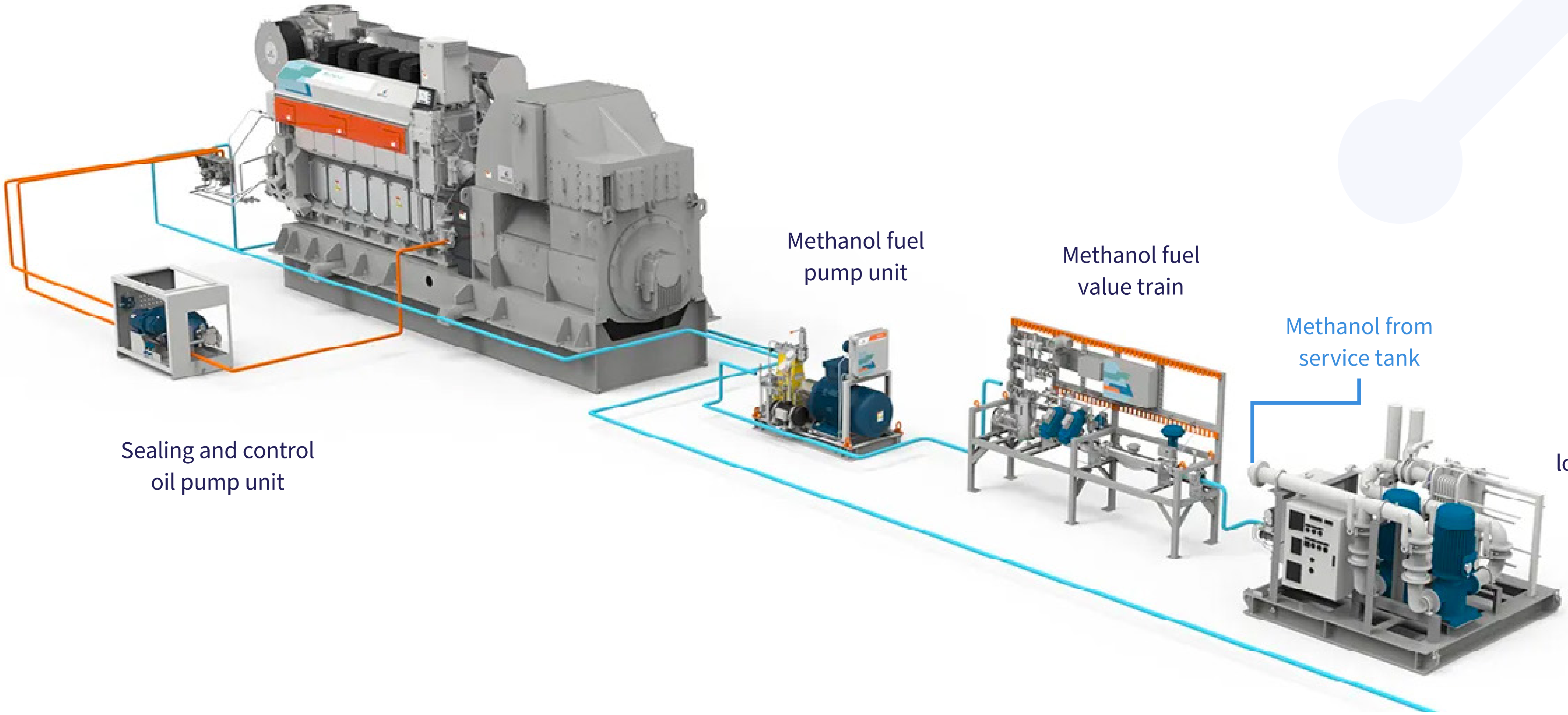
Specialised methanol fuel supply lines and pumps will be needed to deliver the fuel from tank to engine. These are the key systems on the market and are considered mature.

Alfa Laval Fuel Conditioning Module (FCM)

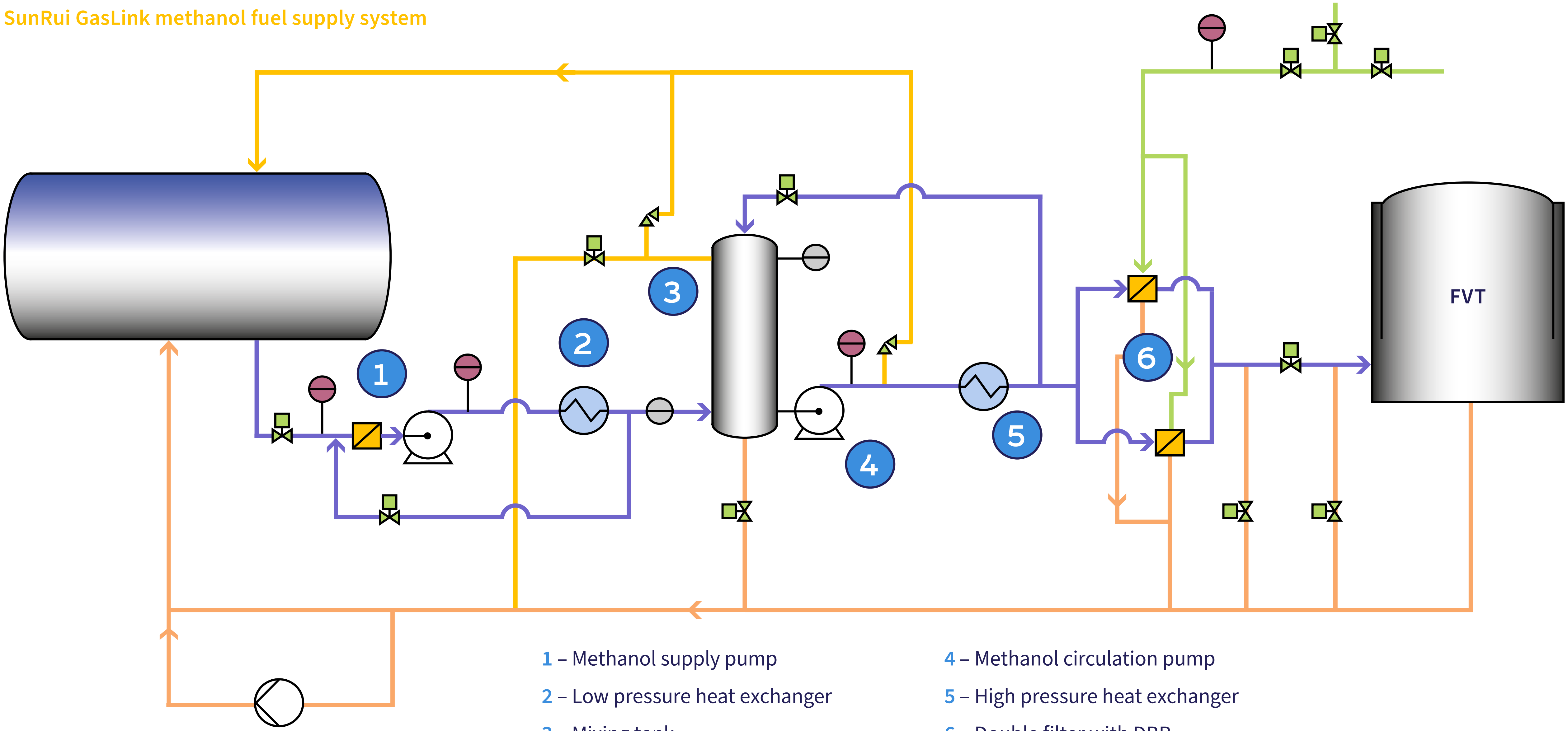
CSSC – Shanghai Marine Diesel Engine Research



Wärtsilä – MethanolPAC



SunRui GasLink methanol fuel supply system



1 – Methanol supply pump
2 – Low pressure heat exchanger
3 – Mixing tank
4 – Methanol circulation pump
5 – High pressure heat exchanger
6 – Double filter with DBB

5.4

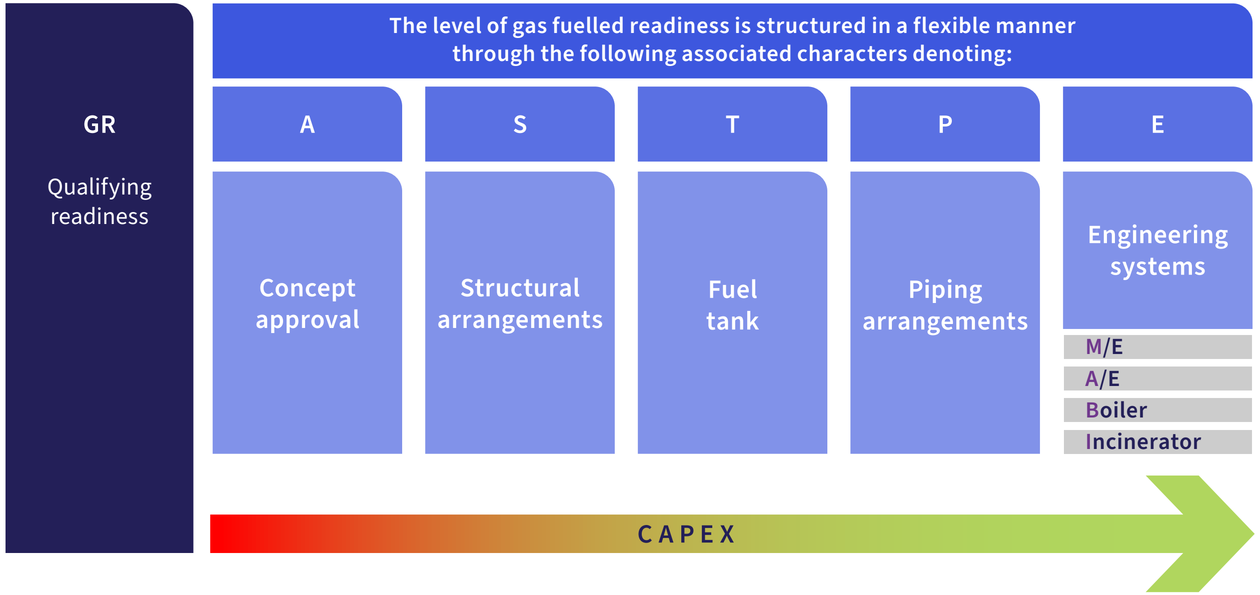
Readiness notations

Capital investment decisions are based on market conditions and vessel demands. These include charter agreements and fuel costs. Flexibility in design parameters is important to enable vessels to be built for an economic lifetime of up to 30 years. Ensuring newbuild contracts are flexible and suitable for future fuel conversions is important and why a Gas Ready notation is available.

The available notations adjacent help owners in their capital investment decisions and therefore in easing future retrofit decisions. Vessels can be ordered to be fuel flexible and designed in a manner that gives them the option to be retrofitted to one of many future fuels.

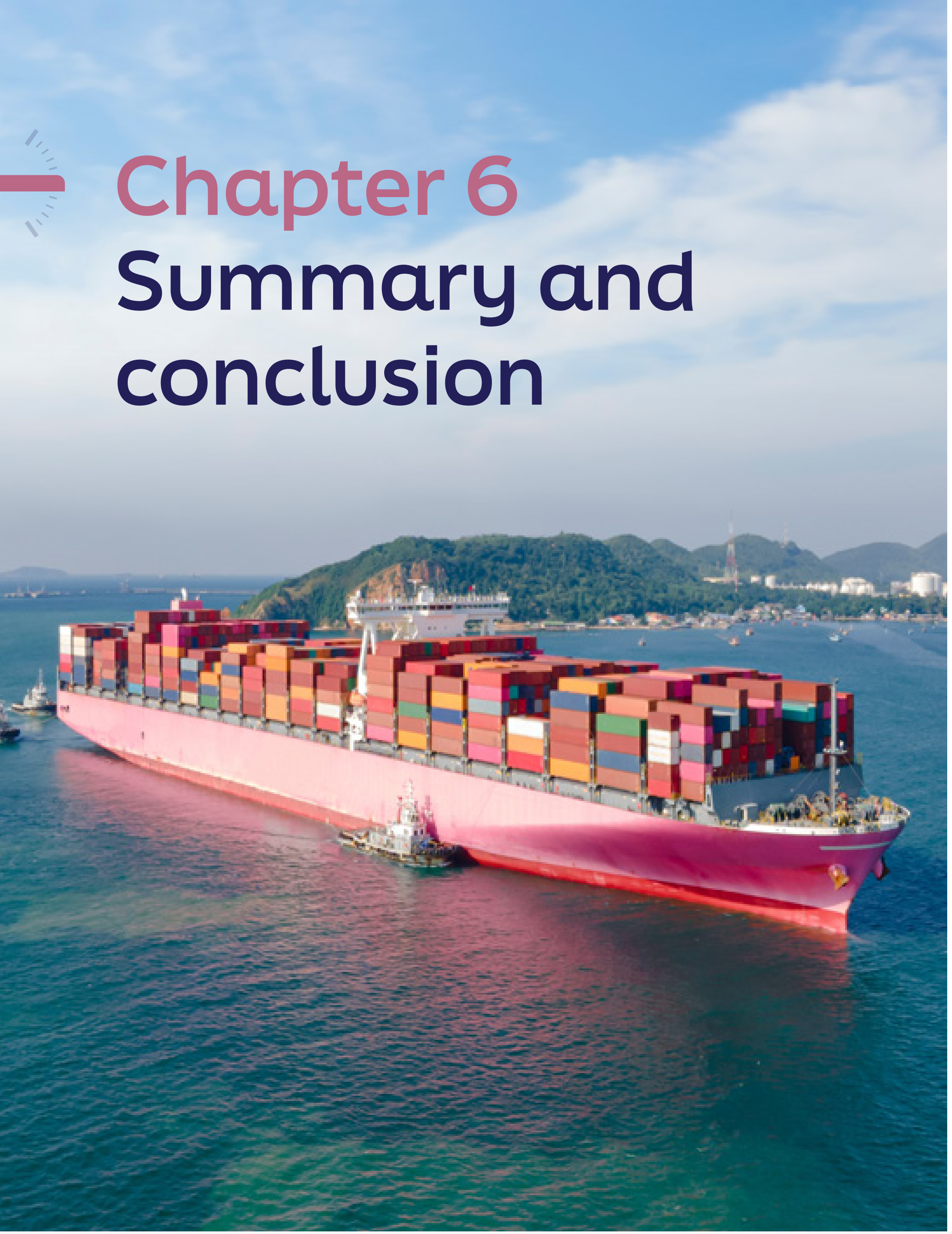
The descriptive note would represent an approval of a conceptual design and/or installation by LR and it is possible that the flag administration may or may not accept the use of a toxic fuel or the conceptual design. A gas ready descriptive note begins with GR and is assigned with the applicable fuel identifier – ML (methanol), AM (ammonia) or NG (natural gas) – followed by a suffix identifying the particular aspects which have been approved and/or installed as shown opposite.

Lloyd's Register has an easy to follow 'gas ready notation' for owners wishing to place orders for newbuildings while reducing the risks related to future fuel choices.



A	Concept approval. The design of the fuel system has been approved in principle
S	Enhanced structural reinforcement fitted to support fuel tank
T	Fuel tank installed
P	Piping installed
E	Equipment and machinery installed M/E – Main engine A/E – Auxiliary boilers Boiler Incinerator Fuel cell generator

Chapter 6
Summary and conclusion



Of the future fuels under consideration by commercial shipping, methanol is unique in that it can be viewed as both an established fuel and a new candidate. It has been used by some vessels for a number of years, but to be a viable environmental solution, fuel production now needs to shift towards renewable rather than fossil methanol. The technology to use methanol as a fuel is feasible, and in many scenarios it is available and mature. All engine makers already have or shall soon have dual fuel engine models imminently, whether two-stroke or four-stroke, diesel or Otto cycle.

Methanol has less energy density compared to current diesel and fuel oils, at a ratio of about 1:2.25. Therefore, on a ton-by-ton basis a vessel would require nearly two and a half times more methanol as fuel oil for a specific consumption. As methanol is a liquid fuel at ambient temperature and pressure, it requires minimal fuel tank specifications, but safety and health arrangements remain important.

Due to the experiences already recorded of transporting methanol as a cargo, and of using it as a fuel for the last decade, safe bunkering guidance has been written and will lead to probable international safety requirements. Class regulations are also in place for newbuilding and retrofit designs to ensure existing safety requirements are met by methanol-powered vessels. As we have seen in the technology readiness chapter, engine designs are maturing rapidly and class societies and engine makers, as well as engineering firms and repair yards, are also building up vital maintenance experience as more engines come into service.

Unsurprisingly, the biggest questions for the further development of methanol as a fuel relate to pricing, availability and carbon accounting. Due to the low production of green methanol and the current orderbook there is speculation over the actual amount of fuel that will be available for shipping, and whether it will be certified green to ensure that the GHG emissions are accounted for on a life cycle assessment basis. **These are all areas that Lloyd's Register will continue to follow closely and cover in future updates to this guide**.

7.1

Chapter 7
Other resources and annexes

Links and other resources

Safety

- IMO interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel
- Health risks of methanol: US National Institute for Occupational Safety and Health (NIOSH)
- Methanol Institute: Methanol safe handling manual
- CWA (European Committee for Standardisation (CEN) Workshop Agreement) on Methanol Bunkering processes (downloadable PDF)
- IAPH Clean marine fuels working group portal
- Port of Amsterdam/DNV safety study on different clean fuels: Bunker verification scheme
- Safetytech Accelerator and Lloyd's Register Maritime Decarbonisation Hub establish a partnership in green fuel assurance – Safetytech Accelerator
- ISO standard AWI 6583 Specification of methanol as a fuel for marine applications
- International Methanol Producer and Consumer Association specifications https://www.impca.eu/IMPCA/Methanol

Supply of green methanol

- Cornell University, 2021: How Green is Blue Hydrogen?
- Methanol Institute: Renewable Methanol
- World Ports Sustainability Program (WPSP): Port Readiness Level for Alternative Fuels for Ships (PRL-AFS)
- Methanol Institute Sees Renewable Methanol Production Growth
- Methanol Market services Asia is an MI member and assesses the global supply/demand and pricing figures (Jan 2020 to Jan 2023)
- Insight briefing: Methanol as a scalable zero emission fuel Getting to Zero Coalition/Global Maritime Forum. Insight briefing 2021

Technology

- Fraunhofer: Obtaining hydrogen from methanol: Optimized reformers
- Progress in Energy and Combustion Science: Methanol as a fuel for internal combustion engines
- European Technology and Innovation Platform: Methanol
- World Ports Sustainability Program (WPSP): Methanol as a fuel
- International Energy Agency (IEA): The IEA data work on calorific values
- U.S. Department of Energy: Fuel Properties Comparison
- MAN ES technical specification of methanol duel-fuelled engine
- LR Zero Readiness Framework

7.2

Annexes

Annex 1: Technology, investment and community readiness levels and definitions

There are three readiness levels used in this report: technology, investment and community. All are on a scale, with TRL on a scale of one to nine, and CRL and IRL on a scale of one to six.

Technology readiness

The technology readiness level indicates the maturity of a solution within the research spectrum from the conceptual stage to being marine application-ready. It is based on the established model used by NASA and other agencies and institutes, using a nine-level scale.

Level	Technology Readiness Level (TRL)	
1	Idea	Basic principle observed
2	Concept	Technology concept formulated
3	Feasibility	First assessment feasibility concept and technologies
4	Validation	Validation of integrated prototype in test environment
5	Prototype	Testing prototype in user environment
6	Product	Pre-production product
7	Pilot	Low-scale pilot production demonstrated
8	Market introduction	Manufacturing fully tested, validated and qualified
9	Market growth	Production and product fully operational

Investment readiness

The investment readiness level indicates the commercial maturity of a marine solution on the spectrum from the initial business idea through to reliable financial investment. It addresses all the parameters required for commercial success, based on work by the Australian Renewable Energy Agency (ARENA). The six-level scale used summarises the commercial status of the solution and is determined by the available evidence in the market.

	INVESTMENT READINESS LEVEL (IRL)	
1	Idea	Hypothetical commercial proposition
2	Trial	Small-scale commercial trial
3	Scale up	Commercial scale up
4	Adoption	Multiple commercial applications
5	Growth	Market competition driving widespread development
6	Bankable asset	Bankable asset class

More details on the readiness levels adopted by Lloyd's Register can be found on the LR Maritime Decarbonisation Hub zero carbon fuel monitor.

Community readiness

The community readiness level indicates the societal maturity of a marine solution in terms of acceptability and adoption by both people and organisations. It is gauged on the spectrum from societal challenge through to widespread adoption. CRL is based on the work by ARENA and Innovation Fund Denmark adapted to a six-level scale.

	COMMUNITY READINESS LEVEL (CRL)	
1	Challenge	Identifying problems and expected societal readiness, formulation of possible solution(s) and potential impact
2	Testing	Initial testing of proposed solution(s) together with relevant stakeholders
3	Validation	Proposed solution(s) validated, now by relevant stakeholders in the area
4	Piloting	Solution(s) demonstrated in relevant environment and in cooperation with relevant stakeholders to gain initial feedback on potential impact
5	Planning	Proposed solution(s) as well as a plan for societal adaptation completed and qualified
6	Proven solution	Actual project solution(s) proven in relevant environment

Annex 2: Table of green methanol production projects (from Methanol Institute)

Capacity (t/y)	Company	Country	Feedstock	Product	Start-up year
80000	Celanese, Mitsui & Co	USA	Recycled CO_2	E-methanol	2022
550000	New Hope Energy	USA	Pyrolized plastic	Biomethanol	2026
300000	Orsted, Maersk	USA		E-methanol	2025
110000	Methanex	USA	Biogas – mass balance approach	Biomethanol	2021
875000	Trans World Energy	USA	Biomass/MSW	Biomethanol	2026
300000	European Energy, Maersk	USA		E-methanol	2025
400	Air Company	USA	Biogenic CO_2 and H_2 from water electrolysis	E-methanol	2020
200000	OCI*	USA	Biogas injection	Biomethanol	2020
	Proman	Trinidad & Tobago	MSW	Biomethanol	
200000	Perstorp	Sweden	CO_2 and H_2 from water electrolysis	E-methanol	2025
50000	Liquid Wind	Sweden	Upcycled CO_2 and H_2 from water electrolysis	E-methanol	2024

***Source:** OCI

Capacity (t/y)	Company	Country	Feedstock	Product	Start-up year
5250	Södra	Sweden	Black liquor	Biomethanol	2021
100000	VärmlandsMetanol	Sweden	Biomass	Biomethanol	2027
220000	Enerkem	Spain	MSW	Biomethanol	2026
100000	Iberdrola and Foresa	Spain	CO_2 and H_2 from water electrolysis	E-methanol	2027
10000	Iberdrola and Foresa	Spain	CO_2 and H_2 from water electrolysis	E-methanol	2026
120,000	Earth and Wire, Enertrag, 24 Solutions	South Africa	Biogenic CO_2 and H_2 from water electrolysis	E-methanol	2027
50000	Air Liquide, PTT Exploration & Production, YTL PowerSaya, Kenoil, Maersk, YTL PowerSaya	Singapore	Biogenic CO_2 and H_2 from water electrolysis	E-methanol	2024
20000	Proman and Global Energy Group	Scotland	CO_2 and H_2 from water electrolysis	E-methanol	2026
100000	CRI, Finnfjord, and Statkraft	Norway	CO_2 from ferrosilicon plant and H_2 from water electrolysis (hydropower)	E-methanol	2025
50000	Glocal Green AS	Norway	Biowaste, bio CO_2 and H_2	Biomethanol	2024

Capacity (t/y)	Company	Country	Feedstock	Product	Start-up year
80000	Swiss Liquid Future/ Thyssenkrupp	Norway	CO_2 from ferrosilicon plant and H_2 from water electrolysis (hydropower)	E-methanol	2027
100000	Glocal Green AS	Norway	Biowaste, bio CO_2 and H_2	Biomethanol	2025
120000	LowLands Methanol	Netherlands	MSW	Biomethanol	2023
15000	Nouryon, Gasunie, BioMCN, Hinicio, McPhy, DeNora	Netherlands	CO_2 and H_2 from water electrolysis	E-methanol	2026
60000	OCI/BioMCN	Netherlands	Biogas	Biomethanol	2020
87500	Gidara Energy	Netherlands	Non-recyclable Waste	Biomethanol	2024
90000	Gidara Energy	Netherlands	MSW	Biomethanol	2024
100	Osaka University, Air Water Hokkaido, and Iwata Chizaki	Japan	Cow manure	Biomethanol	2024
125000	Alia Servizi Ambientali	Italy	CO_2 and H_2 from Waste	E-methanol	2027
115000	ENI	Italy	MSW	Biomethanol	2024
20	NTPC	India	CO_2 and H_2 from water electrolysis	E-methanol	

Capacity (t/y)	Company	Country	Feedstock	Product	Start-up year
40	Municipal Corporation of Gurugram (MCG)	India	Biomass/MSW	Biomethanol	2023
27000	NTPC Renewable Energy, GACL	India	Biogenic CO_2 and H_2 from water electrolysis	E-methanol	
	PCC, SE, Landsvirkjun	Iceland	CO_2 from Silicon Plant	E-methanol	
4000	CRI	Iceland	Geothermal CO_2 and H_2 from water electrolysis	E-methanol	2011
6000	ZASt	Germany	CO_2 and H_2 from water electrolysis	E-methanol	2023
200000	Dow	Germany	CO_2 and H_2 from water electrolysis	E-methanol	2027
	EDF Germany, Holcim Germany, OGE, Ørsted, Raffinerie Heide, Stadtwerke Heide, Thyssenkrupp Industrial Solutions and Thüga	Germany	CO_2 from cement plant and H_2 from water electrolysis (wind)	E-methanol	
	BASF	Germany	Second Generation Raw Materials and Waste	Biomethanol	2020
	TotalEnergies, Sunfire, and Fraunhofer Center for Chemical-Biotechnological Processes CBP	Germany	CO_2 and H_2 from water electrolysis	E-methanol	
61000	Hy2Gen	Germany	CO_2 from biogas and H_2 from water electrolysis	E-methanol	2025

Capacity (t/y)	Company	Country	Feedstock	Product	Start-up year
8000	Apex Energy Teterow GmbH and East Energy Verwaltungs GmbH	Germany		Biomethanol	2027
15000	Wacker Chemie and Linde	Germany	CO_2 and H_2 from water electrolysis	E-methanol	2024
200000	Vycat and Hynamics	France	CO_2 from cement plant and H_2 from water electrolysis	E-methanol	2025
12000	Veolia , Metsa	Finland	Refining and Purifying Crude Methanol obtained from of Kraft Pulping Process	Biomethanol	2024
12000	Veolia and Metsä Fibre	Finland	Black liquor	Biomethanol	2024
300000	Vordingborg Biofuel ApS	Denmark	Straw	Biomethanol	2024
32000	European Energy	Denmark	CO_2 and H_2 from water electrolysis	E-methanol	2027
10000	ReIntegrate	Denmark	CO_2 from biogas plant and H_2 from water electrolysis	E-methanol	2023
32000	European Energy	Denmark	CO_2 and H_2 from water electrolysis	E-methanol	2025
32000	European Energy	Denmark	CO_2 and H_2 from water electrolysis	E-methanol	2027

Capacity (t/y)	Company	Country	Feedstock	Product	Start-up year
150000	Ørsted, SAS, Copenhagen Airports, A.P. Moller – Maersk, DFDS and DSV, with Nel, Haldor Topsøe and Everfuel	Denmark	CO_2 and H_2 from water electrolysis	E-methanol	2035
75000	Ørsted, SAS, Copenhagen Airports, A.P. Moller – Maersk, DFDS and DSV, with Nel, Haldor Topsøe and Everfuel	Denmark	CO_2 and H_2 from water electrolysis	E-methanol	2027
75000	Ørsted, SAS, Copenhagen Airports, A.P. Moller – Maersk, DFDS and DSV, with Nel, Haldor Topsøe and Everfuel	Denmark	CO_2 and H_2 from water electrolysis	E-methanol	2026
75000	European Energy	Denmark	Electrolysis	E-methanol	2025
200	CiP	Denmark	CO_2 and H_2 from water electrolysis	E-methanol	2027
30000	European Energy	Denmark	Electrolysis and CO_2 from Biogas Plants	E-methanol	2023
40000	Shanxi Jia Xin	China	Forestry Waste	Biomethanol	2025
1000	Shenergy	China	Renewable Energy and Carbon Capture	E-methanol	2024

Capacity (t/y)	Company	Country	Feedstock	Product	Start-up year
50000	Shanghai Green Technology	China	Biomass and MSW	Biomethanol	2024
100000	Sinopoc	China	Renewable Energy and Carbon Capture	E-methanol	2024
100000	Energy and Chemical Co., Sinocoal	China	CO_2 and H_2 from water electrolysis	E-methanol	2027
5000	Lu Xi Chemical	China	By Product hydrogen and Carbon Capture	E-methanol	2024
100000	CRI and Jiangsu Sailboat Petrochemicals	China	CO_2 and H_2 from water electrolysis	E-methanol	2023
100000	CRI and Jiangsu Sailboat	China	By Product Hydrogen from PDH + Carbon Capture	E-methanol	2025
1000	Dalian Institute of Chemical Physics	China	CO_2 and H_2 from water electrolysis (PV)	E-methanol	2020
100000	SPIC	China	Renewable Energy and Carbon Capture	E-methanol	2024
100000	Sinocoal	China	Renewable Energy and Carbon Capture	E-methanol	2024
100000	CHN Energy	China	Renewable Energy and Carbon Capture	E-methanol	2024

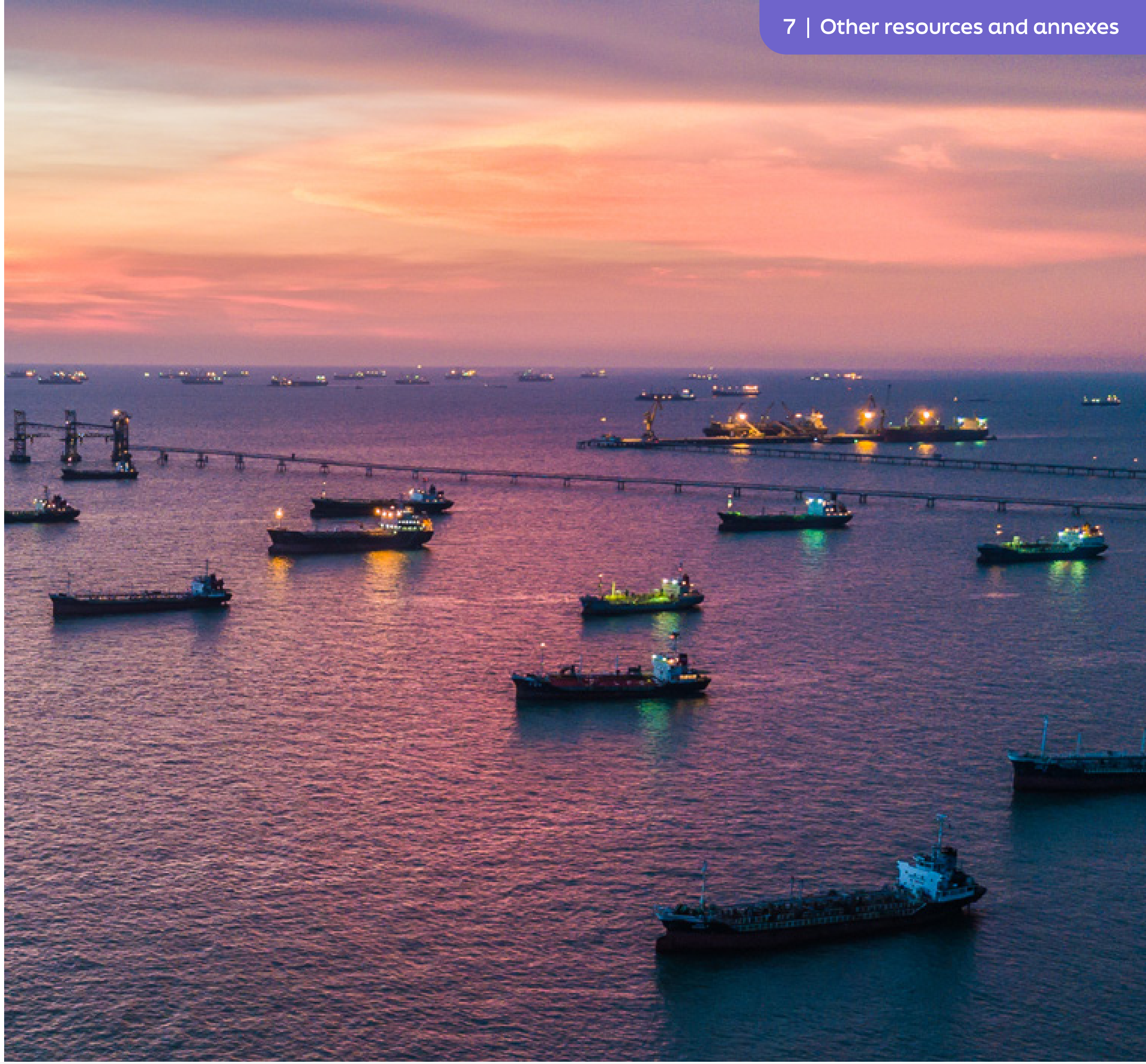
Capacity (t/y)	Company	Country	Feedstock	Product	Start-up year
5000	China Blue Chemical of CNOOC	China	By Product Hydrogen and Carbon Capture	E-methanol	2020
50000	CIMC Enric, Maersk	China	Biomass	Biomethanol	2024
50000	Maersk, GTB	China	Green H_2 and CO_2	Biomethanol	2024
200000	Maersk, Debo	China	Agricultural Residues	Biomethanol	2024
476000	Siemens, Porshe, HIF	Chile	Produced from water, wind energy and CO_2 captured from the air	E-methanol	2026
650	Siemens, Porshe, HIF	Chile	Produced from water, wind energy and CO_2 captured from the air	E-methanol	2022
150000	Andes Mining and Energy (Commercial)	Chile	DAC CO_2 and H_2 from water electrolysis (wind)	E-methanol	2024
100000	Proman, Shell, Suncor, Enerkem, Hydro-Quebec	Canada	Non-recyclable municipal solid waste	E-methanol	2025
30000	Enerkem	Canada	MSW	Biomethanol	2014
500000	Renewable Hydrogen Canada (RH2C)	Canada	CO_2 and H_2 from water electrolysis (hydropower)	E-methanol	2027

Capacity (t/y)	Company	Country	Feedstock	Product	Start-up year
150000	Renewable Hydrogen Canada (RH2C)	Canada	CO_2 and H_2 from water electrolysis (hydropower)	E-methanol	2025
2000	Alberta Pacific	Canada	Black liquor	Biomethanol	2020
30000	WasteFuel, Maersk	Brazil		Biomethanol	2024
44000	Proman, North Sea Port, POM Oost-Vlaanderen, Oiltanking, Fluxys, Engie, ArcelorMittal, Alco Bio Fuel,PMV, Mitsubishi Power	Belgium	Industrial CO_2 and H_2 from water electrolysis (wind power)	E-methanol	2024
8000	ENGIE, Fluxys, Indaver, INOVYN, Oiltanking, Port of Antwerp, PMV	Belgium	CO_2 and H_2 from water electrolysis	E-methanol	2023
265000	VTT	Austria	Black liquor	Biomethanol	2027
200000	ABEL and Thyssenkrupp	Australia	Biogenic CO_2 and H_2 from water electrolysis	E-methanol	2025

Annex 3: Selected methanol related projects to build up industry knowledge and comfort

There are several projects over the last decade that have helped raise industry knowledge and build a methanol roadmap where shipowners feel capable of placing orders, and ports and other infrastructure actors can build the required green bunker supply chains.

- **Stena Germanica – see inset box on** **page 31**
- **Fastwater** (with Lloyd's Register and Methanol Institute), funded by the European Horizon 2020 programme: https://www.fastwater.eu
- **Effship**, 2009 to 2013: www.effship.com
- **Greenpilotv**, a Swedish project to convert a pilot tender to use methanol as a fuel. The purpose of the project was to demonstrate the value of methanol as a marine fuel for smaller vessels and was a continuation of the Summeth project.
- **SPIRETH** (with Lloyd's Register), 2014: https://www.nordicenergy.org/wp-content/uploads/2012/03/Poster_SPIRETH.pdf
- **Collaboration**, initiated by ScandiNAOS AB with the purpose to test in full onboard scale (Stena Scanrail) and in testbed, methanol and di-methyl ether (DME) as fuel and how to handle onboard. The latter to serve as input to development of rules for highly flammable fuel onboard. Participants: ScandiNaos, SSPA, Stena, Haldor Topsoe, LR, Wärtsilä, Methanex.
- **LeanShips** (with Lloyd's Register), 2019: https://www.leanships-project.eu/demo-cases/demo-case-05/overview
- **MethaShip**
- **SUMMETH**, ended 2017: http://summeth.marinemethanol.com



Annex 4: Zero ready framework

Shipowners need to make their own decisions regarding their decarbonisation journey. Decisions are based on their own economic modelling, assessments of readiness and market conditions. This framework, with details found in the LR white paper: Zero Ready Framework helps owners standardise this process.

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

Annex 5: Methanol types table

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

Annex 6: Data assumptions for assessing costs for the switch to methanol

Total cost of ownership case study

Year	2026	2030	2040
Annual MGO Consumption (mt)	10,298.01	514.90	514.90
Annual MGO Cost (USD)	10,246,519.32	576,627.39	774,938.99
Methanol Uptake (%)	0%	95%	95%
Annual Methanol Consumption (mt)	_	20,991.90	20,991.90
Annual Methanol Cost (USD)	–	18,472,869.35	12,175,300.25
TOTAL FUEL BILL (USD)	**10,246,519.32**	**19,049,496.74**	**12,950,239.24**

Year	2026	2030	2040
Annual CO_2e TtW (mt)	33,015.42	1,650.77	1,650.77
Annual CO_2e WtW (mt)	39,347.46	1,967.37	1,967.37
FuelEU CO_2 tax (USD)	**56,496.09**	-	-
EU ETS CO_2 Tax (USD)	**3,598,680.57**	**214,600.22**	**330,154.18**
Global CO_2 tax (USD)	-	**165,077.09**	**165,077.09**
Total CO_2 tax (USD)	**3,655,176.66**	**379,677.31**	**495,231.27**
Total Fuel Bill + CO_2 tax (USD)	13,901,695.98	19,429,174.04	13,445,470.51

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