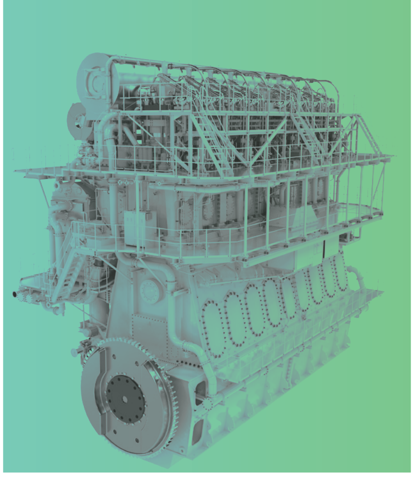
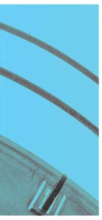
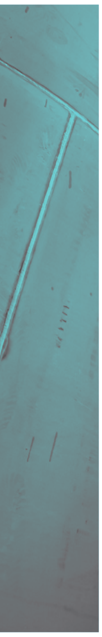


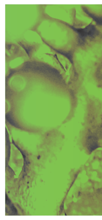
METHANOL INSTITUTE

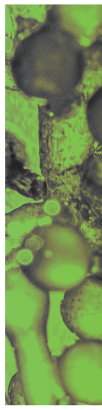
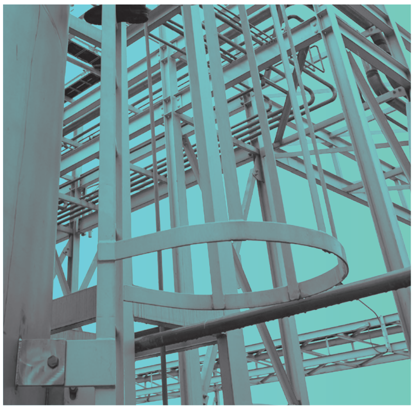
# MARINE METHANOL

## Future-Proof Shipping Fuel


This report provides information on how methanol can help the shipping industry navigate the transition towards low carbon and carbon neutral shipping in a cost-effective and practical manner.

# MARINE METHANOL
## Future-Proof Shipping Fuel

Main author: Carlos Marquez

Case studies: Jason Deign

Design and Typesetting: Henrik Williams, Chrysalis Graphics

**Acknowledgements**
This report was prepared by Carlos Marquez for the Methanol Institute, under the guidance of Greg Dolan (CEO) and Chris Chatterton (COO) from the Methanol Institute.

The authors would like to thank the following companies for their contributions: AP Moller-Maersk, Argo Pte Ltd Shipbrokers, Bureau Veritas, Mariner Communications, Methanex Waterfront Shipping, Mitsui, Proman, Stena Teknik, S&P Commodity Insights.



Citation: Methanol Institute (May 2023), Marine Methanol: Future-Proof Shipping Fuel

# Contents

# Table of Figures

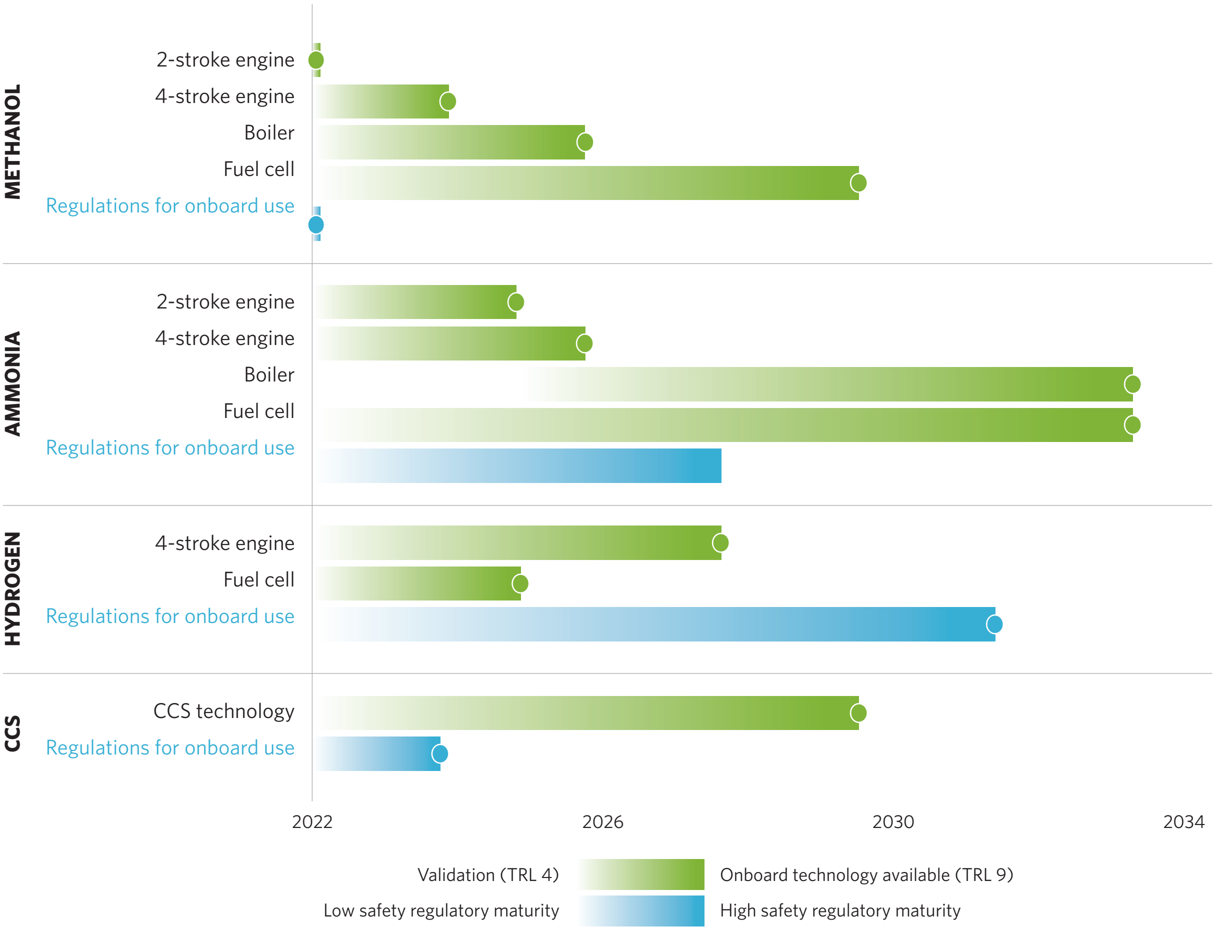
# Executive Summary

**Methanol is a well-known fuel that ship operators can deploy today to reduce pollutant emissions and set themselves on a path to carbon neutrality**. Methanol engines, fuel supply technology and bunkering solutions are commercially available today. Leading shipping companies have already chosen marine methanol including AP Moller-Maersk, CMA CGM, COSCO, Methanex Waterfront Shipping and Stena, to name just a few. A list of methanol vessels can be found in Methanol Vessels on the Water and on the Way.

Safety procedures have also been developed for marine methanol and included in the IMO's Code of Safety for Ships using Gases or other Low Flashpoint Fuels. From a technical perspective, methanol can already be adopted for use onboard ships on a large scale and is five to six years ahead of alternative marine fuels such as ammonia.

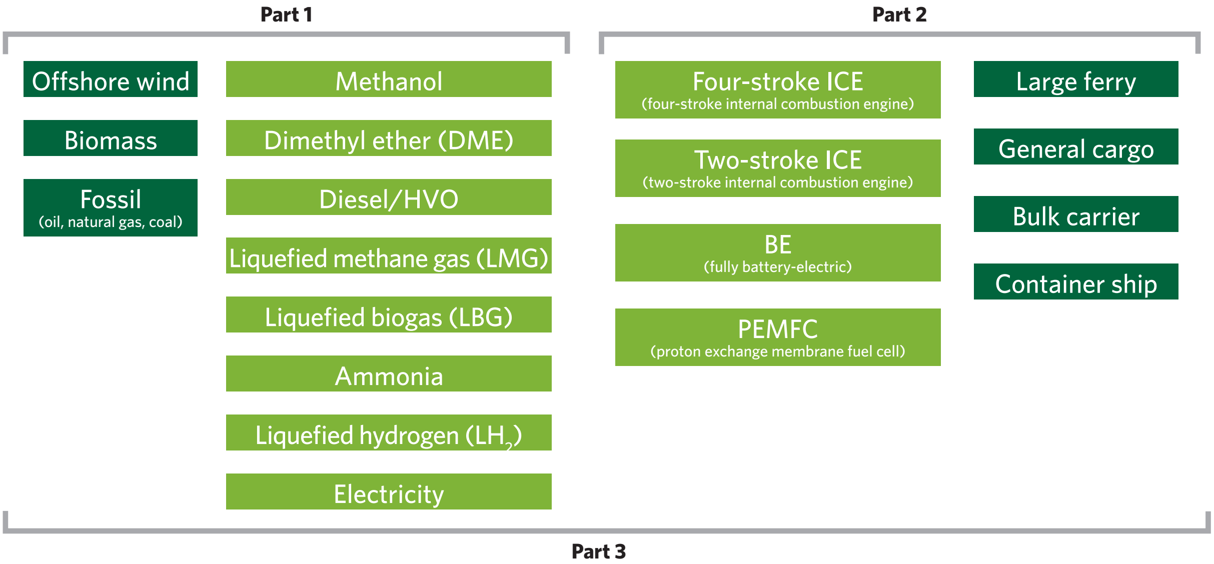
Today, conventional methanol produced from the steam reformation of natural gas is cost competitive with diesel bunker fuels on an energy adjusted basis and is a globally traded commodity. Owners can operate ships on gray methanol today significantly lowering emissions of conventional pollutants, such as $SO_X$, $NO_X$, and PM, while transitioning to blue and green methanol as those fuels become more widely available.

**Figure 1. Expected Availability of Alternative Marine Fuel Technologies - DNV Estimates**




Source: DNV, 2022

**Figure 2. Marine Fuels, Propulsion Technologies, and Ship Types and Usage Considered in the Aalborg and Chalmers University Study (2021)**




Note: Fossil fuels are not assessed but included as a comparison Source: Brynolf, S., Grahn, R., Korberg, A., & Skov, I. (2021, May).

**Methanol is the lowest cost carbon-neutral shipping fuel, by total cost of ownership (TCO), across a wide range of vessels and applications when compared to a suit of fuels including ammonia, liquefied biogas, electricity and hydrogen**, according to a 2021 study by Aalborg University and Chalmers University.

Bio-methanol achieved the lowest TCO across four ship types and all utilization rates, although costs were significantly higher than those of MGO, which was used as a benchmark. The study concludes that regardless of which fuels prevail, "the shipping sector must be ready to pay a significantly higher price for a renewable fuel on a fuel market with generally higher prices than today".

**Market-based measures must be deployed alongside efficiency measures to enable the transition to low carbon shipping fuels, because low and net carbon neutral maritime fuels are currently two to eight times more expensive than conventional fuels**. On the current trajectory, by 2050 the total cost of ownership of vessels that run on net carbon neutral maritime fuels is likely to remain higher than that of fossil-powered vessels (see Figure 3)[1]. The carbon price that experts suggest would enable net-zero shipping by 2050 ranges from \$91 to \$230 per ton of $CO_2$, depending on the policy mechanism chosen. If a flat levy is applied, the average price of $CO_2$ would be at the higher end of the spectrum, whilst a lower average price could be achieved under a return-and-earmark scheme, whereby revenues collected are used to compensate early adopters of low carbon shipping fuels.

**Methanol has a higher energy density than other alternative shipping fuels, including LNG, ammonia, and hydrogen**; when considering the size of storage tanks, secondary barriers, and cofferdams. However, the energy density of methanol is lower than that of traditional shipping fuels. For example, MGO has an energy density of 36.6 GJ/$m^3$ compared to methanol's 15.8 GJ/$m^3$.This means that on a methanol-powered ship, storage and fuel tanks take about 2.4 times more space than on ships that run on MGO. This disadvantage is mitigated by frequent bunkering and by the fact that methanol can be stored in conventional fuel storage tanks and even ballast tanks on-board a vessel, unlike fuels such as LNG and $H_2$ that require cryogenic storage[2] and have a greater impact on the loss of cargo space.

1 Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. (2021, October). We show the world it is possible. Retrieved May 2, 2022 from Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping: https://cms.zerocarbonshipping.com/media/uploads/documents/MMMCZCS_Industry-Transition-Strategy_Oct_2021.pdf

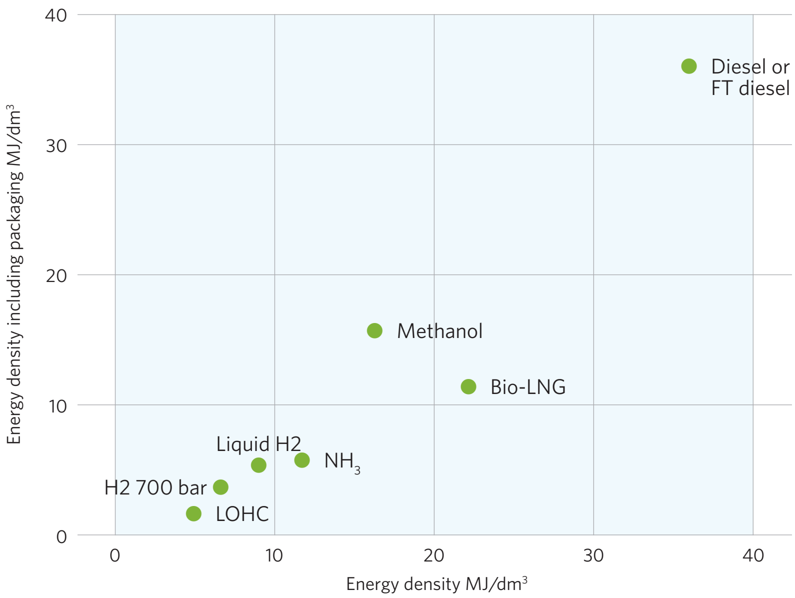
2 IRENA. (2021). A pathway to decarbonise the shipping sector by 2050. Abu Dhabi: International Renewable Energy Agency. Retrieved November 19, 2022, from https://irena.org/publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050

## Figure 3. Estimated Total Cost of Ownership (TCO) of Vessels by Type of Fuel

**Path we are on: estimate total cost of ownership across various vessel types[i]**


Source: Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021
Note: Hydrogen is not considered fuel-suitable for deep-sea shipping because of immaturity in safe usage, storage and conversion of hydrogen as an onboard fuel.
[i] Typical vessels refer to: Container: 8,000 TEU capacity; Tanker: LR2 85 - 125k DWT; Bulk carrier: Panamax 70-99k DWT. Typical operation profiles have been assigned to each vessel type.
[ii] Uses pyrolysis oil availability and cost projections.

## Figure 4. Energy density of different fuel types

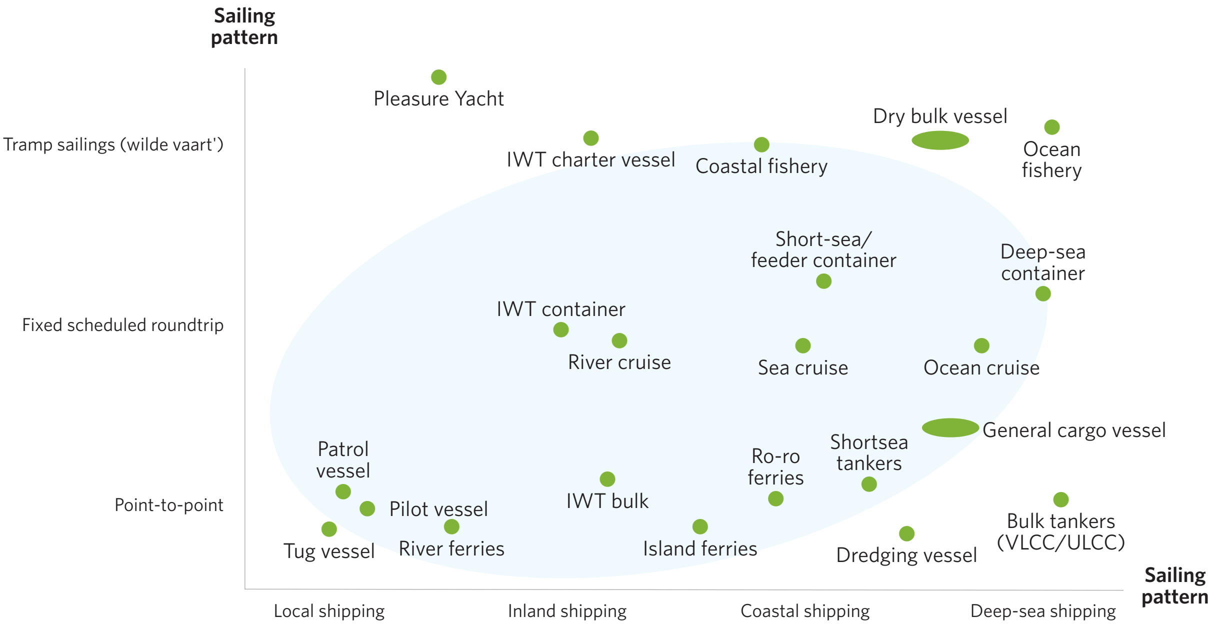



Source: Green Maritime Methanol, 2021

**Methanol is suitable for a wide range of shipping applications, including cruise ships, inland waterway bulk transport vessels, short-sea container ships, ferries, short-sea tankers, deep-sea container vessels and general cargo vessels**, according to research by TNO[3]. Although only 20 percent of the vessels are engaged in deep sea shipping, they make up 80 percent of bunker fuel demand.

3 Zomer, G., Finner, S., Harmsen, J., Vredeveldt, L., & van Lieshout, P. (2020). Green Maritime Methanol: Operation aspects and the fuel supply chain. The Hague: TNO. Retrieved November 19, 2022, from https://publications.tno.nl/publication/34637282/W1qAIG/TNO-2020-R11105.pdf

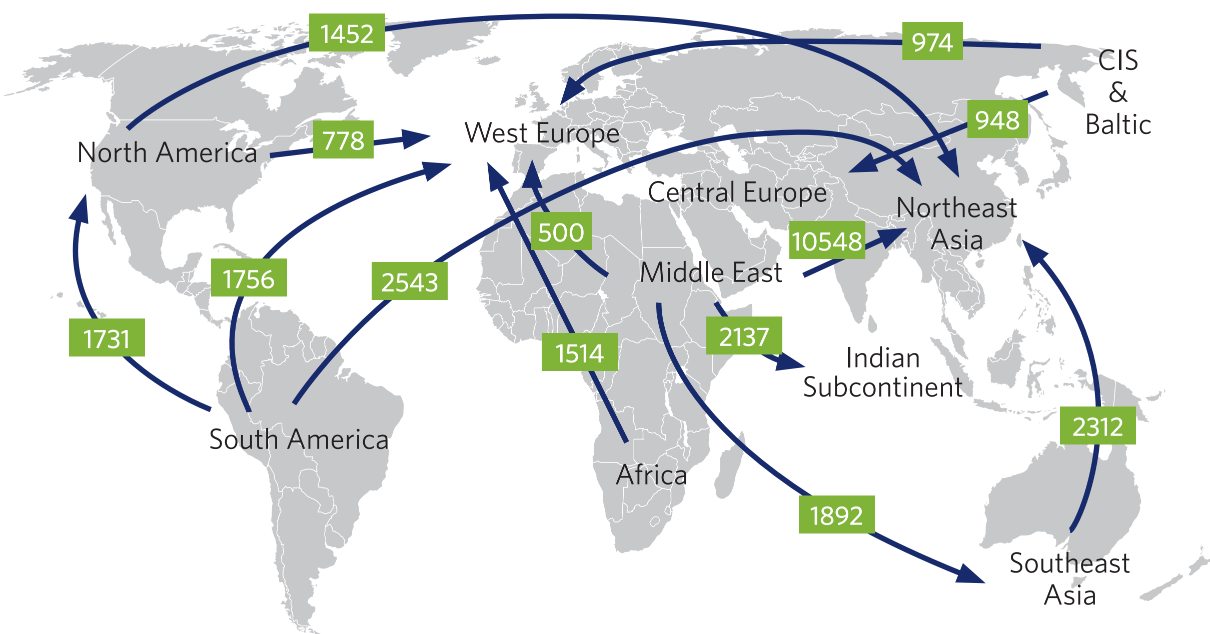
### Figure 5. Heatmap of methanol shipping applications




Source: Green Maritime Methanol, 2021

**Methanol is available at over 120 ports worldwide and shipped globally**. Today, there are more than 90 methanol production facilities around the world with an aggregate ~120 million tons of production capacity, fully capable of meeting today's ~100 million tons[4] of methanol demand. Once produced, about a third of this methanol is shipped and traded globally as an industrial commodity[5], with the majority of methanol being consumed domestically or transported to neighboring markets and hubs over land.

### Figure 6. Main Methanol Interregional Trade Flows (Thousand metric tons per annum)




Source: Chemical Market Analytics

4 Ton means metric ton throughout the report, unless otherwise specified.
5 "The Methanol Industry." Methanol Institute, 2022, https://www.methanol.org/the-methanol-industry/. Accessed 2 May 2022.

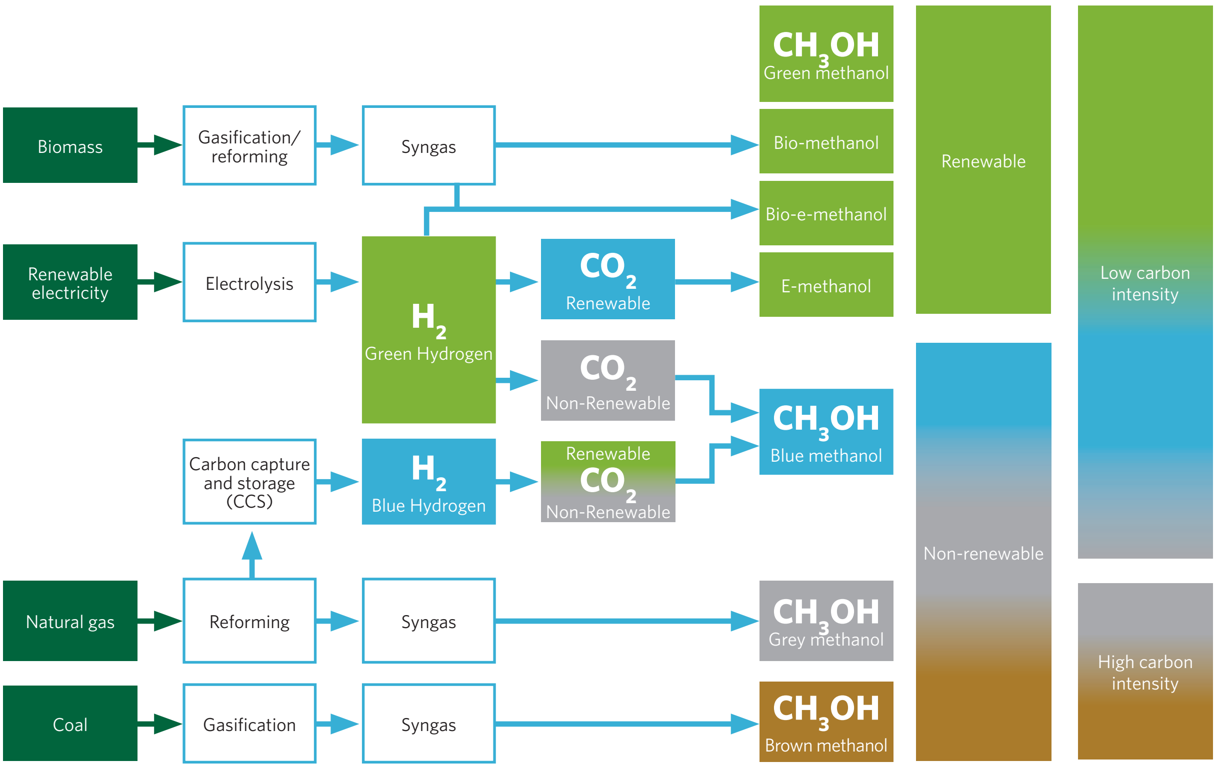
**Deploying methanol as a marine fuel dramatically lowers emissions of sulfur oxides ($SO_x$), nitrogen oxides ($NO_x$) and particulate matter (PM) compared to Heavy Fuel Oil (HFO) or Marine Gas Oil (MGO)**. Methanol combustion itself does not generate any $SO_x$ or PM emissions, and what little emissions do occur come from a small amount of diesel (3-5 percent) deployed as pilot fuel. Ship operators can immediately comply with the IMO's most stringent $SO_x$ and PM emissions regulations by switching to methanol. According to tests carried out by MAN Energy Solutions, operators can reduce $NO_x$ emissions below Tier III levels by deploying a mixture of methanol with 25 to 40 percent of water, and 3-5 percent of diesel as a pilot fuel.

Marine methanol emissions reductions vs HFO/MGO

**$SO_x$ -99% PM -95% $NO_x$** Up to **-80%**

**Methanol can be produced from biomass, bio-methane, renewable electricity plus $CO_2$, and from fossil sources such as natural gas and coal**. Most methanol is currently produced from natural gas, where natural gas is used both as a feedstock and as a process fuel.

**Figure 7. Methanol Production Pathways**

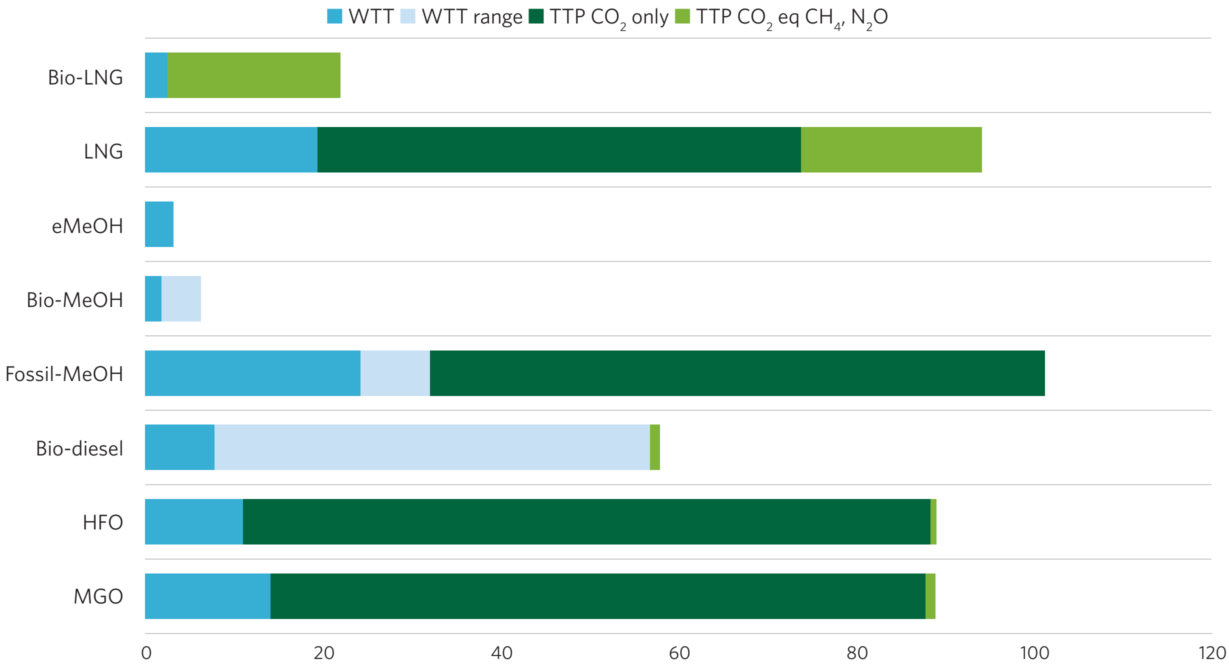



Source: IRENA and Methanol Institute, 2021

**The carbon intensity of methanol varies depending on the feedstock and the production pathway used**. Once well-to-propeller emissions are included, bio-methanol (bio-MeOH) and e-methanol (eMeOH) are among the shipping fuels with the lowest emissions.

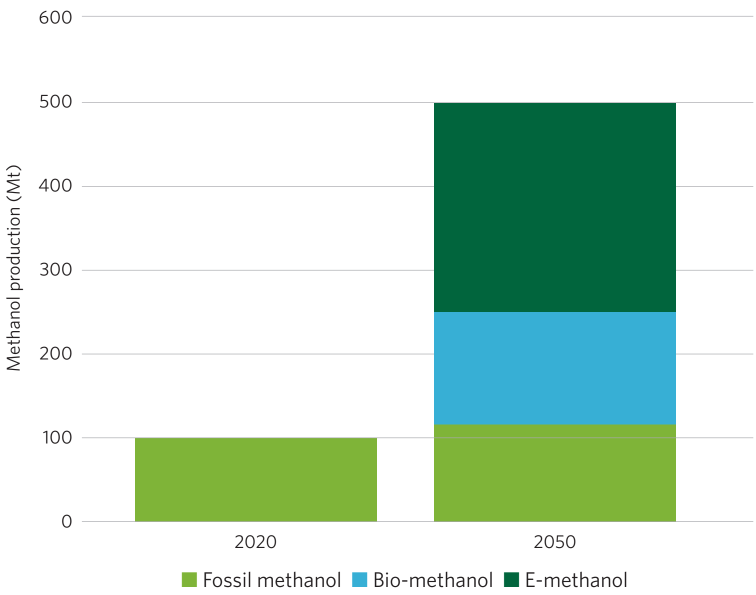
**Methanol production is expected to increase five-fold to 500 million tons per year by 2050, with bio-methanol and e-methanol making up 80 percent of total production**, according to IRENA.

**Figure 8. Well-to-Propeller Emissions of Different Fuels ($gCO_2eq/MJ$)**




Note: WTT: Well-to-Tank; TTP: Tank-to-Propeller Source: Green Marine Methanol Consortium

**Figure 9. Methanol Production by 2050**




Source: IRENA

**Methanol bunkering, or refueling, is very similar to MGO or HFO bunkering**. Methanol remains liquid at ambient temperature and pressure, which means that the same infrastructure that is used to store and bunker traditional marine fuels can be used for methanol, after minor and inexpensive modifications.

**Safety guidelines and regulations for methanol use onboard ships have already been developed**. Methanol is toxic to humans, meaning that crews must be appropriately trained on how to handle a methanol leak. Essentially, methanol is handled more like gasoline than diesel fuels.

### Figure 10. Barge-to-Ship Methanol Bunkering at the Port of Rotterdam

Source: Waterfront Shipping

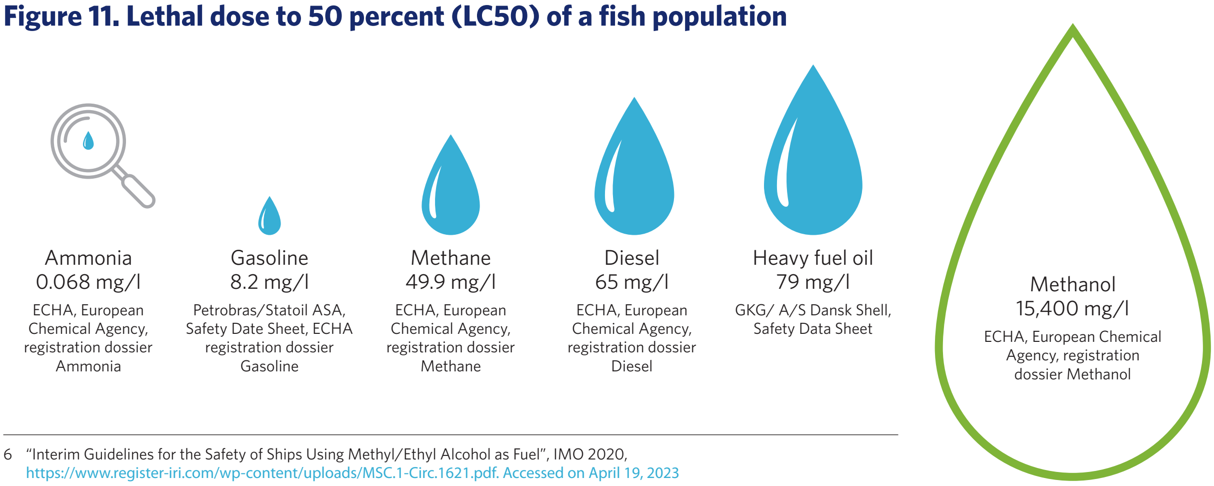
Additionally, measures must be taken to prevent and contain fires, as methanol is a low-flashpoint fuel, tends to accumulate close to the ground and does not dissipate in enclosed unventilated areas.

These characteristics call for specific safety measures that prevent methanol vapors from forming and the installation of appropriate ventilation, leak detection, heat detection and fire extinguishing equipment. Measures to prevent methanol fires in a marine environment are well known in the chemical industry and have been adopted in the Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel[6]. It is worth mentioning that it took six years of work to formulate these guidelines and they were finally approved by the IMO in November 2020. Other alternative fuels are just starting this process now.

Methanol is routinely shipped globally and the marine industry has ample experience in handling methanol safely. More information on methanol safety can be found in the Methanol Safe Handling Manual (5th edition).

**Methanol is fully miscible in water and biodegradable; in case of a spill, the effects on marine life are very likely to be temporary and fully reversible**. Many other marine fuels, including HFO, methane and ammonia are much more toxic to marine life than methanol.

### Figure 11. Lethal dose to 50 percent (LC50) of a fish population




6 "Interim Guidelines for the Safety of Ships Using Methyl/Ethyl Alcohol as Fuel", IMO 2020, https://www.register-iri.com/wp-content/uploads/MSC.1-Circ.1621.pdf. Accessed on April 19, 2023

# 1.
# Introduction

This report provides an analysis into the use of methanol as a marine fuel considering four key factors: compliance with emissions reduction legislation, track-record, cost, and performance compared to other alternative fuels.

For over a decade, the International Maritime Organization (IMO) has introduced measures to lower emissions of sulfur oxides ($SO_X$), nitrogen oxides ($NO_X$), and particulate matter (PM) in shipping. This has long been a major driver for the adoption of alternative fuels, including methanol.

The IMO also introduced a strategy in 2018 to reduce greenhouse gas (GHG) emissions. This strategy, among other objectives, aims to halve total annual GHG emissions from international shipping by 2050 compared to 2008 levels. This strategy is confirmed to be revised in 2023 at MEPC 80, based on additional market feedback around IMO's various programs. Another organization, the industry-led Cargo Owners for Zero Emission Vessels (CoZev), has set out to eliminate GHG emissions from shipping by 2050.

Methanol is a fuel that shipping companies can deploy today to meet regulations seeking to curb emissions. Compared to heavy fuel oil (HFO), commercially available methanol made from natural gas can slash emissions of $NO_X$ by 80 percent, $SO_X$ by 99 percent, PM by 95 percent. When deployed alongside advanced engines, methanol is compliant with the most stringent emission reduction regulations issued by the IMO[7].

Most methanol, excluding China, is produced from natural gas, but there are companies already producing low and carbon neutral bio-methanol from a variety of widely available renewable feedstocks such as bio-methane, municipal waste, sludge, pulp liquor and agricultural or forestry residues. Other pioneering companies have opted for producing e-methanol by combining hydrogen ($H_2$) produced with renewable electricity with circular $CO_2$ captured from an industrial flue gas source, biogenic $CO_2$, or from direct air capture (DAC).

Compliance with GHG emission reduction legislation is one of the main drivers of the search for alternative fuels, but it is not the only factor. Availability, ease of use, performance, and total cost of ownership all play important roles as key enablers. On all these counts, methanol offers significant advantages.

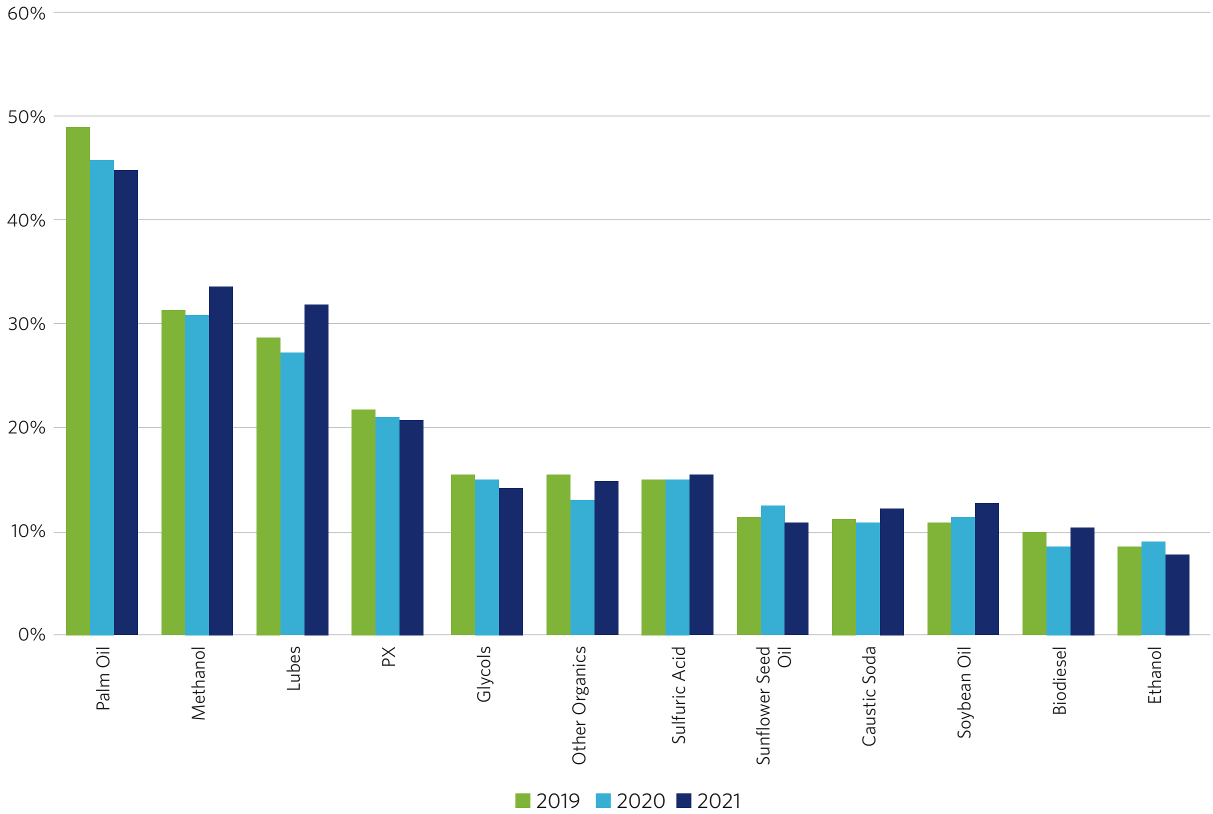
Today, there are more than 90 methanol production facilities around the world with an aggregate ~120 million tons of production capacity, fully capable of meeting today's ~100 million tons[8] (33 billion gallons or 125 billion liters) of methanol demand. Once produced, about a third of this methanol is shipped and traded globally as an industrial commodity[9], with the majority of the product consumed domestically or transported to neighboring markets and hubs over land.

7 Forsyth, Adam, and Longspur Research. All At Sea - Methanol and Shipping. 25 January 2022, https://www.proman.org/wp-content/uploads/2022/01/Methanol-and-Shipping-2501221.pdf. Accessed 2 May 2022.

8 Ton means metric ton throughout the report, unless otherwise specified.

9 "The Methanol Industry." Methanol Institute, 2022, https://www.methanol.org/the-methanol-industry/. Accessed 2 May 2022.

**Figure 12. Most Globally Shipped Chemicals by Volume (Millions of Tons)**




Source: Argo PTE Ltd Shipbrokers

Methanol is easy to handle because it remains liquid at ambient temperature and pressure, unlike other alternative fuels such as LNG, ammonia, or hydrogen. This means that methanol transportation and bunkering is simple and can largely be achieved with existing infrastructure, after relatively simple modifications, in a cost-effective manner. As one of the world's most widely shipped chemical commodities and fuels, methanol storage capacity is available in over 120 ports.

Thanks to its advantages, leading shipping companies have adopted methanol as a marine fuel, with shipping giants AP Moller–Maersk, CMA CGM and COSCO being high-profile examples. At the time of writing, there are more than two dozen methanol-powered vessels in service and more than 80 new two-stroke methanol dual-fuel engines in the order book of MAN Energy Solutions, the leading methanol engine OEM. Other models are now being offered or introduced by established companies such as MAN Energy Solutions, Wärtsilä, Rolls-Royce/MTU, WinGD, Anglo Belgian Corporation (ABC), Caterpillar, and Hyundai Heavy Industries. Dual fuel engines that can run on both diesel fuel and methanol are available, making the transition easier for both newbuilds and retrofitting of existing vessels.

This report provides insight into the pros and cons of methanol as a marine fuel compared to traditional marine fuels and alternatives such as LNG, hydrogen, ammonia, and batteries.

# 2.
# Regulatory Drivers of Methanol as a Marine Fuel

The combustion of standard shipping fuels such as Heavy Fuel Oil (HFO) emits $SO_X$, $NO_X$, particulates, and other pollutants that are harmful to human health and degrade the environment. For this reason, the IMO and other bodies have issued regulations to curb the emission of these pollutants in shipping.

More recently, $CO_2$ emissions from shipping have also come under the attention of regulators. Shipping accounts for 90 percent of global trade and 3 percent of GHG emissions. It remains the most efficient and least polluting form of long-haul transport. However, if no additional measures are taken, emissions from shipping will increase significantly and by 2050 they could make up between 5 and 8 percent of global GHG emissions[10].

This chapter provides information on the role of methanol as a marine fuel in the context of regulations issued by regional and supranational bodies to curb the emission of pollutants and greenhouse gases in shipping.

## 2.1 The IMO's International Convention for the Prevention of Pollution from Ships (MARPOL Annex VI) to Control $SO_X$ and $NO_X$ Emissions

The International Maritime Organization (IMO) is the United Nations (UN) agency responsible for regulating safety, security and polluting prevention in international commercial shipping. In 2000, the IMO first introduced measures under MARPOL Annex VI to lower $SO_X$ and $NO_X$ emissions from shipping.

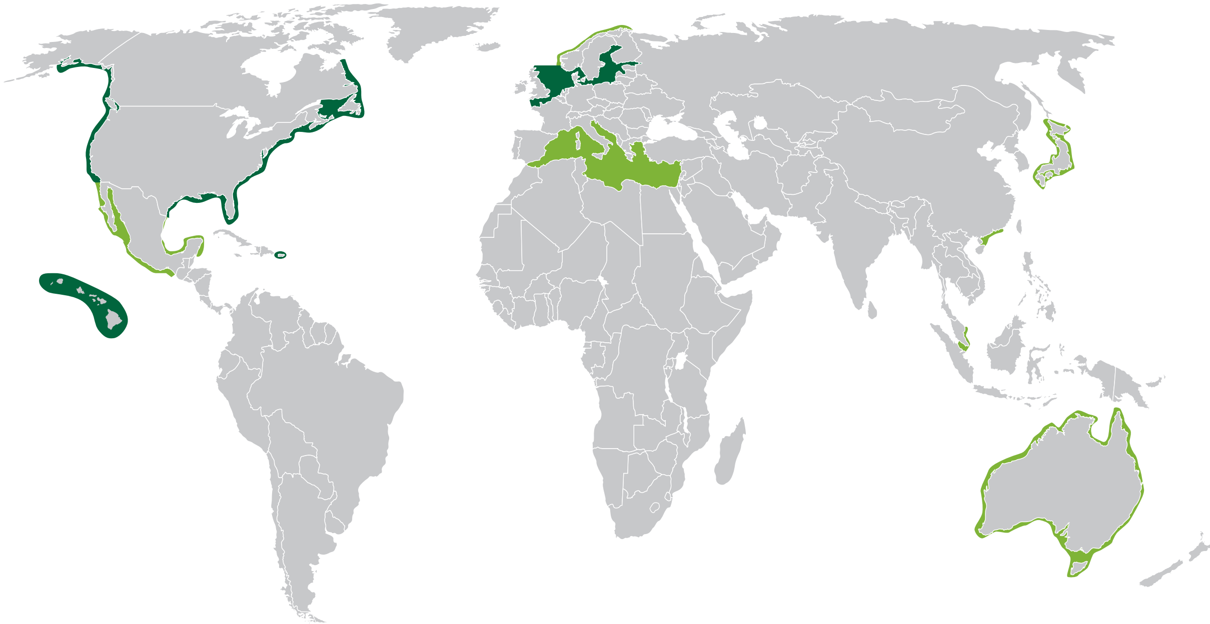
These regulations have been updated regularly since then, with the latest version coming into force in January 2020, which is why it is known in the industry as "IMO 2020." According to IMO 2020, the maximum permitted level of sulfur content in fuel is 0.5 percent, mass by mass (m/m).

Inside designated Emission Control Areas (ECAs), the level of allowable sulfur in fuel is even lower, at 0.1 percent (m/m). ECAs are areas in which pollution from ships is more tightly controlled. There are currently five ECAs around the Baltic Sea, the North Sea, North America, the US Caribbean and the Mediterranean Sea. The Mediterranean Sea ECA for $SO_X$ and PM was designated at the MEPC 79 session in December 2022. This is expected to enter into force on May 1, 2024, with the new limit taking effect from May 1, 2025.

In an effort to curb $NO_X$ emissions in shipping, the IMO has issued regulation 13 of MARPOL Annex VI. According to this regulation, ships with diesel engines of at least 130 kW output power need to be surveyed and certified to ensure that they meet the $NO_X$ limits set in the regulation. These limits vary depending on the ship's construction date and the engine's rated speed (see Figure 14). Tier III $NO_X$ limits, the most stringent, apply to ships built from 2016 onward whilst they are operating within the North America or the US Caribbean ECAs.

10 Mærsk McKinney Møller Center for Zero Carbon Shipping. "We show the world it is possible.", October 2021, https://cms.zerocarbonshipping.com/media/uploads/documents/MMMCZCS_Industry-Transition-Strategy_Oct_2021.pdf. Accessed 2 May 2022.

## Figure 13. Emission Control Areas (ECAs) Worldwide



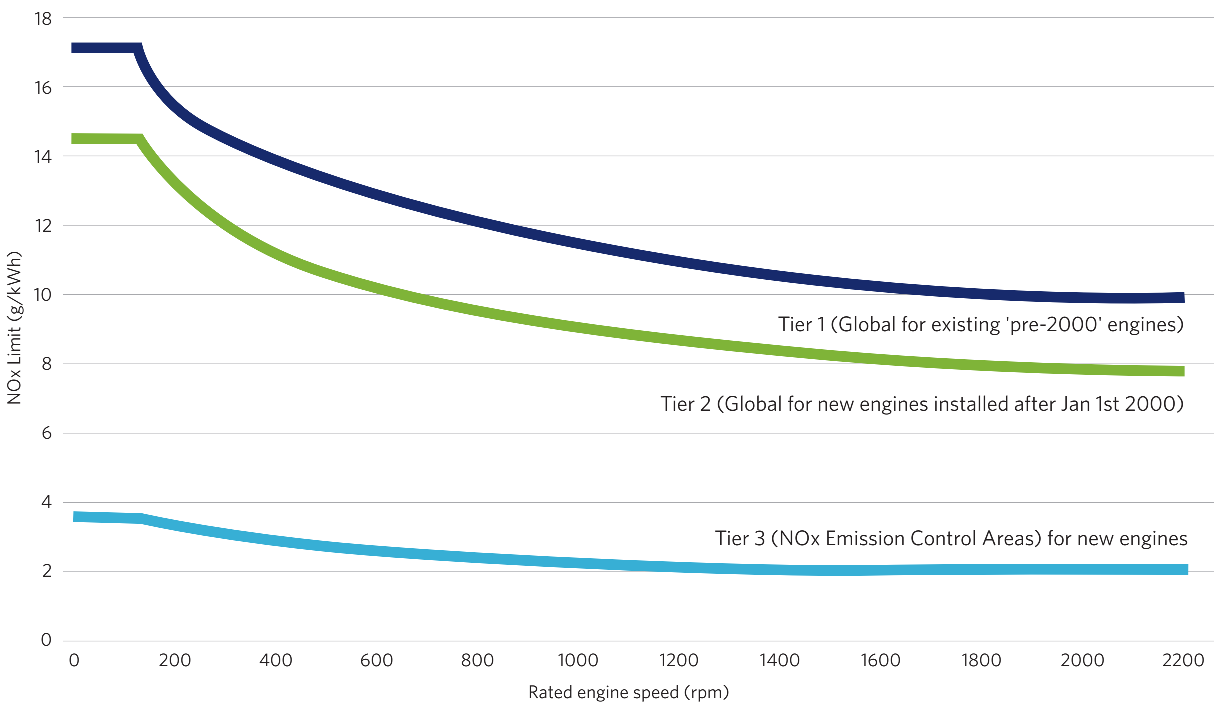
An Emission Control Area can be designated for $SO_x$ and PM or $NO_x$, or all three types of emissions from ships, subject to proposal from a Party to Annex VI.

Existing Emission Control Areas include:
- Baltic Sea ($SO_x$, adopted: 1997/entered into force 2005)
- North Sea ($SO_x$ 2005/2006)
- Baltic Sea and North Sea SECAs (level of $SO_x$ in fuel is set at 0.1% since the 1st of January 2015)
- North American ECA, including most of US and Canadian coast ($NO_x$ and $SO_x$, 2016/2012)
- US Caribbean ECA, including Puerto Rico and the US Virgin Islands ($NO_x$ and $SO_x$, 2011/2014)

- Existing ECA area
- Potential future ECA area

Source: IMO

## Figure 14. Nitrogen Oxide (NOx) Emission Limits According to MARPOL ANNEX VI




Source: IMO

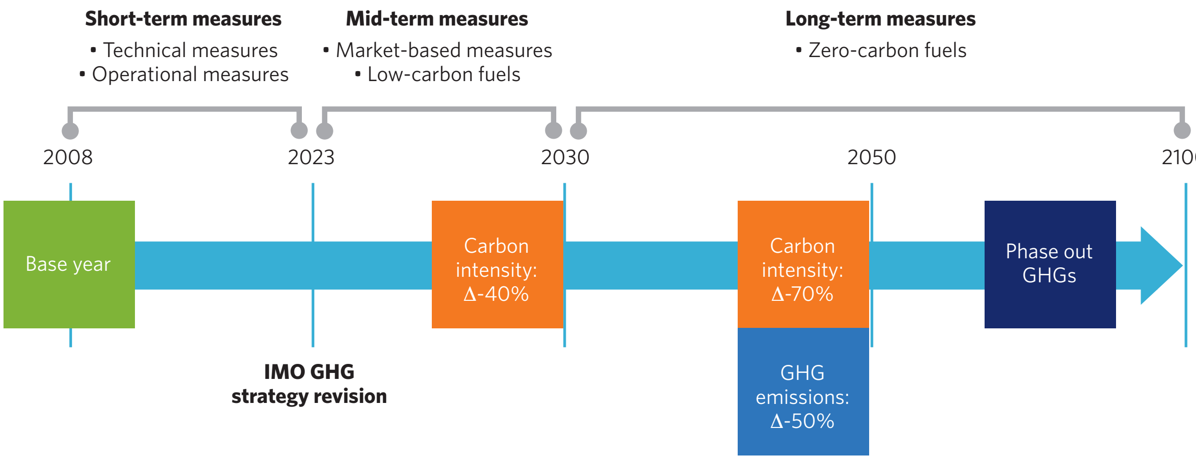
In the case of the Baltic Sea and North Sea ECAs, Tier III $NO_X$ limits apply to ships built from 2021 onward. Outside ECAs, Tier II levels apply. Ships that meet $NO_X$ emissions standards obtain the Engine International Air Pollution Prevention (EIAPP) Certificate[11].

Methanol is a fuel that shipping companies can deploy today to meet regulations seeking to curb emissions. Compared to heavy fuel oil (HFO), commercially available methanol made from natural gas can slash emissions of $NO_X$ by 80 percent, $SO_X$ by 99 percent, and PM by 95 percent. When deployed alongside advanced engines, methanol is compliant with the most stringent emission reduction regulations issued by the IMO.

## 2.2 The IMO's GHG Reduction Strategy

In 2018, the IMO introduced a strategy to reduce GHG emissions in shipping. This includes reducing total annual GHG emissions from international shipping by 50 percent by 2050, compared to 2008 levels. Additionally, the strategy aims to "reduce $CO_2$ emissions per transport work, as an average across international shipping, by at least 40 percent by 2030, pursuing efforts towards 70 percent by 2050, compared to 2008"[12].

**Figure 15. Overview of IMO GHG Emissions Reduction Strategy**




Source: IMO adapted by Bureau Veritas

To achieve these GHG targets, ships are required to improve their energy efficiency by means of retrofitting and by operating efficiently. The regulatory measures employed to address technical energy efficiency improvements in shipping are the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Existing Ship Index (EEXI).

### The Energy Efficiency Design Index (EEDI) and Energy Efficiency Existing Ship Index (EEXI)

The EEDI and EEXI aim to encourage ship design parameters that lead to lower $CO_2$ emissions per transport work.

The EEDI, introduced in 2013, sets minimum energy efficiency levels for each ship type, expressed in grams of $CO_2$ emitted by ton-mile. Using these guidelines, ships are required to develop a Ship Energy

11 "Nitrogen Oxides (NOx) – Regulation 13." *International Maritime Organization*, https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx. Accessed 7 May 2022.

12 "Initial IMO GHG Strategy." *International Maritime Organization*, https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx. Accessed 7 May 2022.

Efficiency Management Plan (SEEMP) to reduce $CO_2$ emissions by improving operational efficiency. The EEDI is being implemented in progressively stricter phases, starting with a 10% reduction in $CO_2$ emissions during phase 0 (2013 to 2015) and arriving at a 30% reduction in $CO_2$ emissions at phase 4 (from 2025 onwards).

The EEDI and the EEXI are very similar. The main difference between them is that the EEDI applies to new ships only and EEXI applies to existing ships.

According the EEXI, ships of 400 gross tonnage (GT) and above must first calculate their existing energy efficiency to establish the attained EEXI. This value is then compared against the required energy efficiency or required EEXI, which is determined for each type of ship. If the attained EEXI is below the required EEXI, the ship must be modified to meet the required EEXI by the next survey for the International Air Pollution Prevention Certificate (IAPPC) or by the time the survey for the International Energy Efficiency Certificate (IEEC) is due. These measures came into force in November 2022[13].

The EEDI and EEXI have their own separate guidelines, but it is expected that they will be consolidated into one set of guidelines[14].

The EEDI and EEXI measure $CO_2$ emissions on a tank-to-wake basis. This means that only $CO_2$ emissions that occur when the fuel is combusted on-board ships are considered. However, GHG emissions do occur during fuel production. Additionally, $CO_2$ is only one of GHG emitted during fuel production, with methane and $N_2O$ being two common pollutants that also occur at this stage. If emissions continued to be regulated on a tank-to-wake basis, there is the danger of promoting the uptake of fuels that generate high emissions during the production process but low emissions during combustion, effectively shifting emissions elsewhere but leaving total GHG emissions unchanged.

The current EEDI and EEXI standards could be made more effective in reducing GHG emissions by applying two modifications: firstly, by measuring emissions of other gases on a $CO_2$ equivalent basis; secondly, by measuring emissions that occur from production to combustion or, as it is known in the industry, on a well-to-wake basis. Should these measures be applied, even gray methanol, from natural gas, would yield lower GHG emissions than alternative shipping fuels such as LNG[15]. $CO_2$ equivalent emissions from bio-methanol and e-methanol would be even lower.

While the EEDI and EEXI address technical efficiency of ships, another measure addresses their operational efficiency, namely the Carbon Intensity Indicator (CII) rating scheme.

### Carbon Intensity Indicator (CII) rating scheme

Under the CII scheme, ships are required to measure and record their actual carbon intensity over a year of operation to obtain the attained annual operational CII. This value is then compared to the required annual operational CII to give a ship a rating on a scale between A and E. Ships that are rated D or E for three consecutive years need to submit a plan of corrective measures to attain

13 "EEXI – Energy Efficiency Existing Ship Index." Lloyd's Register, https://www.lr.org/en/eexi-energy-efficiency-existing-ship-index/. Accessed 7 May 2022.

14 The relation between EEXI, EEDI and Shaft Power Limiters (n.d.). Retrieved February 2, 2023, from Danelec: https://www.danelec.com/insights/blog/the-relation-between-eexi-eedi-and-shaft-power-limiters/

15 Corner & Sathiamoorthy (2022) How updating IMO regulations can promote lower greenhouse gas emissions from ships (ICCT WORKING PAPER 2022-34), International Council on Green Transportation. Retrieved February 7, 2023 from https://theicct.org/publication/marine-imo-eedi-oct22/

an index rating of C or above. The ships performance is recorded in the Ship Energy Efficiency Management Plan (SEEMP)[16] [17].

The CII rating scheme applies from 2023 to all cargo, ropax and cruise vessels of 5000 GT and above that trade internationally. The intention of this scheme is to encourage ships to transport cargo and passengers as efficiently as possible. The requirements for meeting these standards are expected to become more stringent.

### Figure 16. Overview of EEDI, EEXI and CII

<table>
<tr><td>Energy Efficiency Design Index (EEDI)<br>It aims to make ships more efficient. The EEDI has been implemented since January 2013.</td><td>One-time certification.</td><td>Applies to new ships.</td><td rowspan="3">Both the EEXI and the CII come into force in 2023 and apply to the following kinds of ships:<br>■ Bulk carriers<br>■ Gas carriers<br>■ Tankers<br>■ Container ships<br>■ General cargo ships<br>■ Refrigerated cargo carriers<br>■ Combination carriers<br>■ LNG carriers<br>■ Vehicle carriers<br>■ Ro-Ro cargo vessels<br>■ Ro-Ro Passenger vessels<br>■ Cruise ships</td></tr>
<tr><td>Energy Efficiency Existing Ship Index (EEXI)<br>Addresses technical efficiency of existing ships by setting performance standards for ships of a given type, capacity and propulsion system.<br>The main difference is the EEDI applies to new ships only, whereas the EEXI applies to existing ships.</td><td>One-time certification.</td><td>Applies to existing ships of 400 GT and above.</td></tr>
<tr><td>Carbon Intensity Indicator (CII)<br>Addresses operational efficiency of ships.<br>Measures grams of $CO_2$ emitted per cargo-carrying capacity and nautical mile, giving each ship an annual rating between A (best) and E (worst).<br>Ships rated D for three consecutive years, or E in a single year must submit a corrective plan as part of the Ship Energy Efficiency Management Plan.</td><td>Assesses emissions annually.</td><td>Applies to ships of 5000 GT and above.</td></tr>
</table>

Source: BV, DNV and Lloyd's Register

### Upcoming Market Based Measures (MBM): Pricing Carbon Emissions

In May 2022, the IMO established a timetable to work towards a basket of market-based measures (MBM)[18], including putting a price on shipping emissions.

There are several competing carbon pricing methods and levels. AP Moller-Maersk proposed a carbon tax of $450 per ton of fuel, which translates to about $150 per ton of $CO_2$, whereas the Marshall Islands proposed a price of $100 per ton of $CO_2$[19].

Exactly how a price on emissions would be implemented is still under discussion. Some key considerations include the policy mechanisms (Emissions Trading System or "ETS," levy, or feebate) that are to be deployed, whether just $CO_2$ or other types of emissions (methane, nitrous oxide, and black carbon) will be included on a $CO_2$-equivalent basis, and whether the price would be applied to emissions on a tank-to-wake or a well-to-wake basis. Whereas IMO members have not yet decided

16 "CII - Carbon Intensity Indicator." DNV, https://www.dnv.com/maritime/insights/topics/CII-carbon-intensity-indicator/index.html. Accessed 7 May 2022.

17 Forsyth, Adam, and Longspur Research. All At Sea - Methanol and Shipping. 25 January 2022, https://www.proman.org/wp-content/uploads/2022/01/Methanol-and-Shipping-2501221.pdf. Accessed 2 May 2022. Report.

18 12th session of the Intersessional Working Group on Greenhouse Gases (ISWG-GHG 12) took place online between the 16th and 20th of May 2022

19 Muchira, N. (2022, May 27). IMO Breaks Deadlock on Carbon Pricing for Shipping. Retrieved May 29, 2022, from The Martime Executive: https://www.maritime-executive.com/article/imo-breaks-deadlock-on-carbon-pricing-for-shipping

on the exact measures, they all seem to agree that they must be implemented urgently to avoid the worst effects of climate change. Given all the groundwork required, MBM are likely to come into force between 2025 and 2026[20].

This means that it is urgent for the shipping industry to adapt and reduce GHG emissions by becoming more efficient and adopting cleaner fuels. Methanol is a readily available fuel that enables shipping companies to reduce their GHG emissions and provides a clear pathway to net carbon neutral emissions on a well-to-wake basis.

The Methanol Institute has issued a position paper calling on maritime policymakers to adopt a well-to-wake approach to GHG accounting of fuels to support the decarbonization of maritime transport (see: https://www.methanol.org/marine-fuel/). The Methanol Institute believes that an approach that accounts for GHG emissions of the fuel's entire value chain is essential to stimulate the uptake of renewable fuels that can drive the shipping industry's energy transitions.

## 2.3 Proposed Regulation by the European Union: Fit for 55

The European Commission has proposed various measures to lower GHG emissions in shipping, in alignment with the broader EU target of slashing total GHG emissions by 55 percent by 2030, in the "Fit for 55" package. These measures, which have not yet been implemented and are under discussion, include the following:

- **FuelEU Maritime Proposal:** Lowering the carbon intensity of vessels of 5000 GT and above by 6 percent by 2030 and 75 percent by 2050, compared to 2020 and encouraging the uptake of low carbon maritime fuels, as measured on a well-to-wake basis[21].
- **Alternative Fuels Infrastructure (AFIR)**: Supplying electricity to ships at the quayside in ports from 2030
- **Including shipping emissions in the EU Emissions Trading System (EU ETS)**: Ships 5000 GT and above which are trading in EU ports must pay for the emissions generated on a tank-to-wake basis; More stringent requirements could appear from 2027.
- **Energy Taxation Directive**: Eliminating tax exemptions on conventional marine fuels

Including shipping emissions in the EU ETS would put pressure on the maritime industry to reduce emissions. Assuming a price of €80 per EU Allowance (EUA), each of which is equivalent to a ton of $CO_2$, a 9500 twenty-foot equivalent unit (TEU) container vessel that trades with the EU would pay up to €1.6 million per year in carbon credits by 2024. All assumptions on this simplified calculation can be seen in Figure 17.[22]

The full package of measures is comprehensive and its implications complex. Given that these measures have not yet been implemented, this section does not delve into the full ramifications of the proposal. However, it is clear that the EU is seeking to significantly reduce GHG emissions from shipping. The Methanol Institute has issued a series of position papers on the Fit for 55 package which can be found on our website at www.methanol.org/policy-initiatives/europe.

20 Smith, A. S. (2022). An overview of the discussions from IMO SWG-GHG 12. UMAS. Retrieved May 29, 2022 from https://www.u-mas.co.uk/wp-content/uploads/2022/05/ISWG-GHG-overview-UMAS-final.pdf

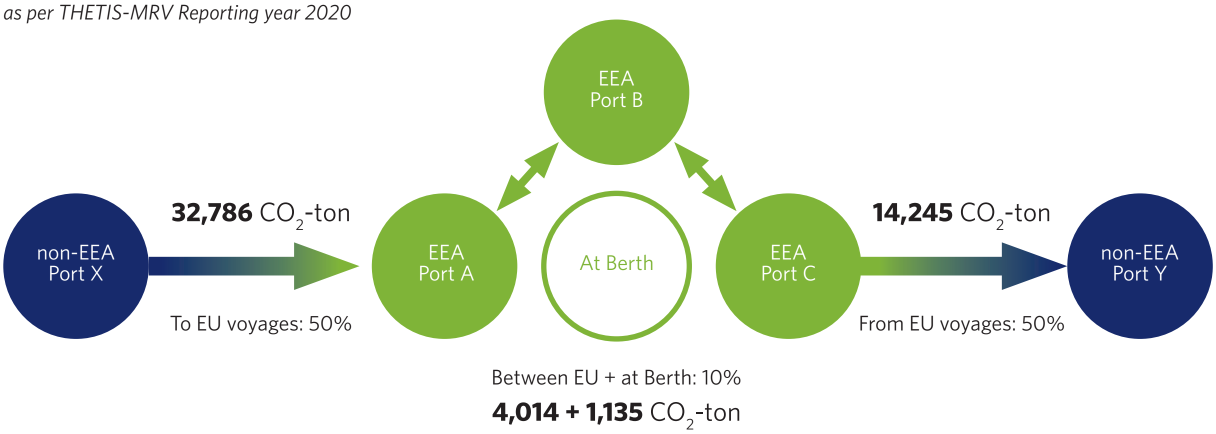
21 Pape, Marketa. "Sustainable maritime fuels." European Parliament, 8 November 2021, https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698808/EPRS_BRI(2021)698808_EN.pdf. Accessed 10 May 2022.

22 Xiaodong, Z. (2022, April). Shipping Efficiency Game 2023 -2030. Lloyd's Register. Retrieved May 05, 2022

**Figure 17. Example of the Cost of Running a Ship Under the EU ETS**

**EU ETS Example: A 9.5k TEU Container Vessel**

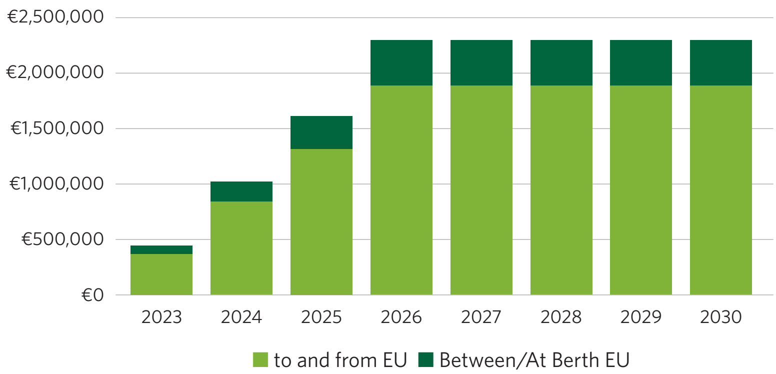
*as per THETIS-MRV Reporting year 2020*




**In 2023, assuming the vessel has a total in-scope emission of:**

32,786 x 50% + 14,245 x 50% + (4,014 x 1,135) x 100% =28,664 $CO_2$-ton ~ 28,664 EUAs to surrender by each April
To simplify this example, we assume that the vessel emits the same amount of $CO_2$ emission year-on-year until 2030.

Emission allowance assumption:
€80 per $CO_2$-ton




Source: Xiadong, 2022

## 2.4 Green Shipping Corridors - The Clydebank Declaration

Originally launched in 2021 at COP26, the Clydebank Declaration aims to achieve net zero emissions in shipping by 2050. This involves establishing zero emission shipping routes, including port infrastructure and vessels. In other words, green shipping corridors.

The Clydebank Declaration has been signed by the following 22 countries: Australia, Belgium, Canada, Chile, Costa Rica, Denmark, Fiji, Finland, France, Germany, Ireland, Italy, Japan, the Republic of the Marshall Islands, Morocco, the Netherlands, New Zealand, Norway, Spain, Sweden, the UK, and the US. More are expected to adhere in the near future.

The shipping corridors announced between Los Angeles and Shanghai and between Antwerp and Montreal are among the first and most significant to date. The solutions implemented and the experiences garnered in these initial green corridors will provide information crucial to rolling out further corridors between the major shipping routes, some of which can be seen in Figure 18.

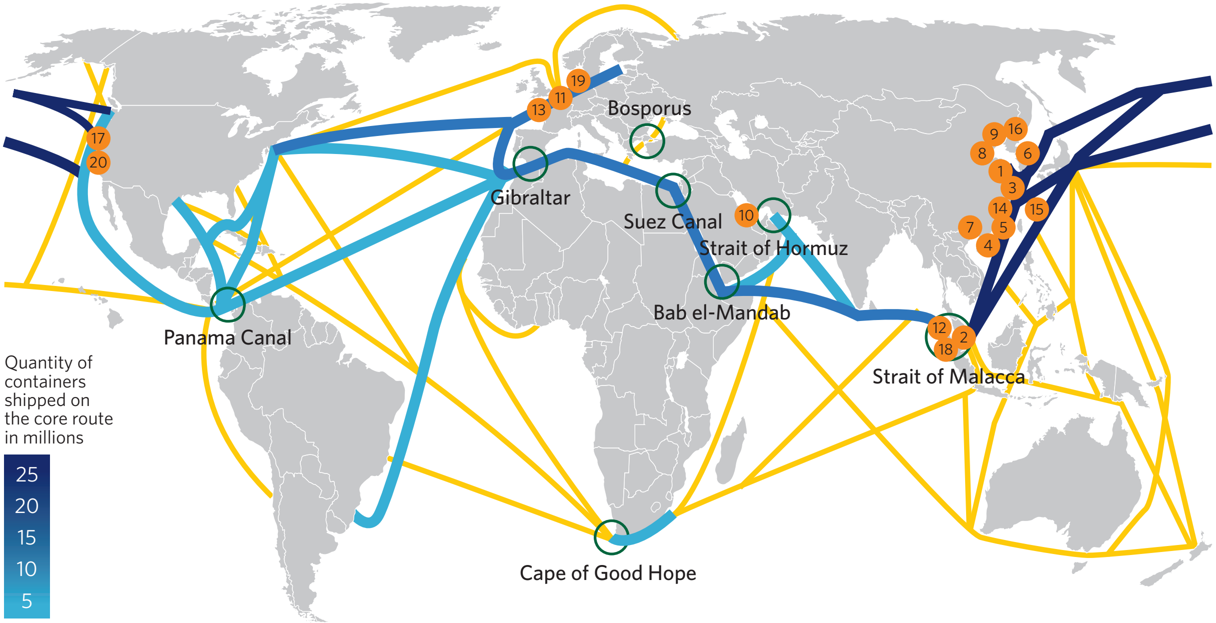
## 2.5 Carbon Pricing

The IMO and the European Commission (EC) are considering applying a carbon price on shipping emissions to enable the transition to net carbon neutral shipping. Factors such as price per ton of $CO_2$, geographic scope, schedule of implementation, and how the revenues from the carbon levy are used will have a decisive impact on the maritime industry.

## Figure 18. Global Maritime Shipping Routes

**Martitime shipping route and their main destinations**

*Worldwide shipping routes and the biggest container ports in 2018*




Core route Secondary route Choke point

**Shipped containers in millions** | **Growth rate in %**

1 Shanghai | **42.0** | **+4.4**
2 Singapore | **36.6** | **+8.7**
3 Ningbo | **26.4** | **+6.9**
4 Shenzhen | **25.7** | **+2.1**
5 Guangzhou | **21.9** | **+7.6**
6 Busan | **21.7** | **+5.5**
7 Hong Kong | **19.6** | **-7.6**
8 Qingdao | **19.3** | **+5.5**
9 Tianjin | **16.0** | **+6.2**
10 Dubai | **15.0** | **-2.9**
11 Rotterdam | **14.5** | **+5.7**
12 Klang | **12.0** | **-0.4**
13 Antwerp | **11.0** | **+6.2**
14 Xiamen | **10.7** | **+3.1**
15 Kaohsiung | **10.5** | **+1.8**
16 Dalian | **9.8** | **+0.6**
17 Los Angeles | **9.5** | **+1.3**
18 Tanjung Pelepas | **8.8** | **-6.4**
19 Hamburg | **8.8** | **-0.2**
20 Long Beach | **8.0** | **+3.7**

Source: Heinrich-Böll-Stiftung European Union, 2021

Low and net carbon neutral maritime fuels are currently two to eight times more expensive than conventional fuels. On the current trajectory, by 2050 the total cost of ownership (TCO) of vessels that run on net carbon neutral maritime fuels is likely to remain higher than that of fossil-powered vessels (see Figure 19)[23]. This means that a price on carbon must be deployed alongside efficiency measures to enable the transition to low carbon shipping fuels.

The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping has estimated how a carbon price can be deployed to enable net carbon neutral shipping. According to their estimates, a flat levy of \$230 per ton of $CO_2$-eq would enable low carbon fuels like methanol to compete and allow shipping to achieve net zero by 2050[24]. Whilst the simplicity of a flat levy plays in its favor, it also places a high burden on the shipping industry by forcing it to pay more than is required for the transition. It has been estimated that this levy would collect cumulative revenues of \$1.8 trillion in excess of what is required to bridge the cost gap between fossil and net carbon neutral fuels.

23 Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. (2021, October). We show the world it is possible. Retrieved May 2, 2022 from Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping: https://cms.zerocarbonshipping.com/media/uploads/documents/MMMCZCS_Industry-Transition-Strategy_Oct_2021.pdf

24 In this analysis, anything below than 0.1 $GtCO_2eq$ is consider net zero emissions

## Figure 19. Estimated Total Cost of Ownership (TCO) of Vessels by Type of Fuel

**Path we are on: estimate total cost of ownership across various vessel types**


Note: Hydrogen is not considered fuel-suitable for deep-sea shipping because of immaturity in safe usage, storage and conversion of hydrogen as an onboard fuel.
[i] Typical vessels refer to: Container: 8,000 TEU capacity; Tanker: LR2 85 - 125k DWT; Bulk carrier: Panamax 70-99k DWT. Typical operation profiles have been assigned to each vessel type.
[ii] Uses pyrolysis oil availability and cost projections.

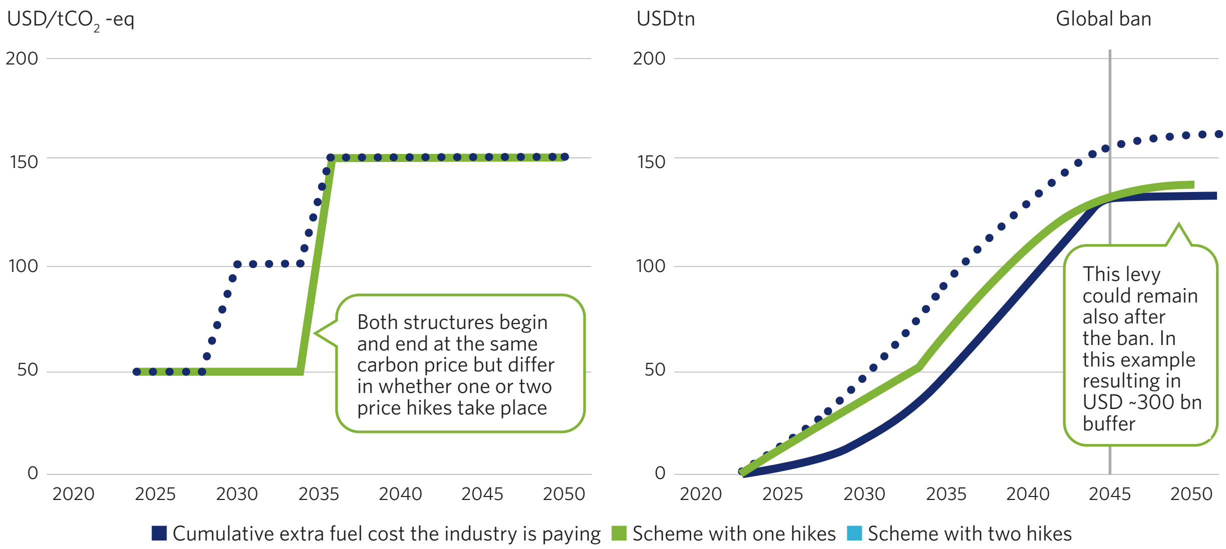
Source: Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021

## Figure 20. Implementation of a return-and-earmark pricing scheme

**Sequenced pricing and bans can level the playing field for industry participants and nations**

The regulator can start by imposing an 'earmark and return' global carbon levy system...

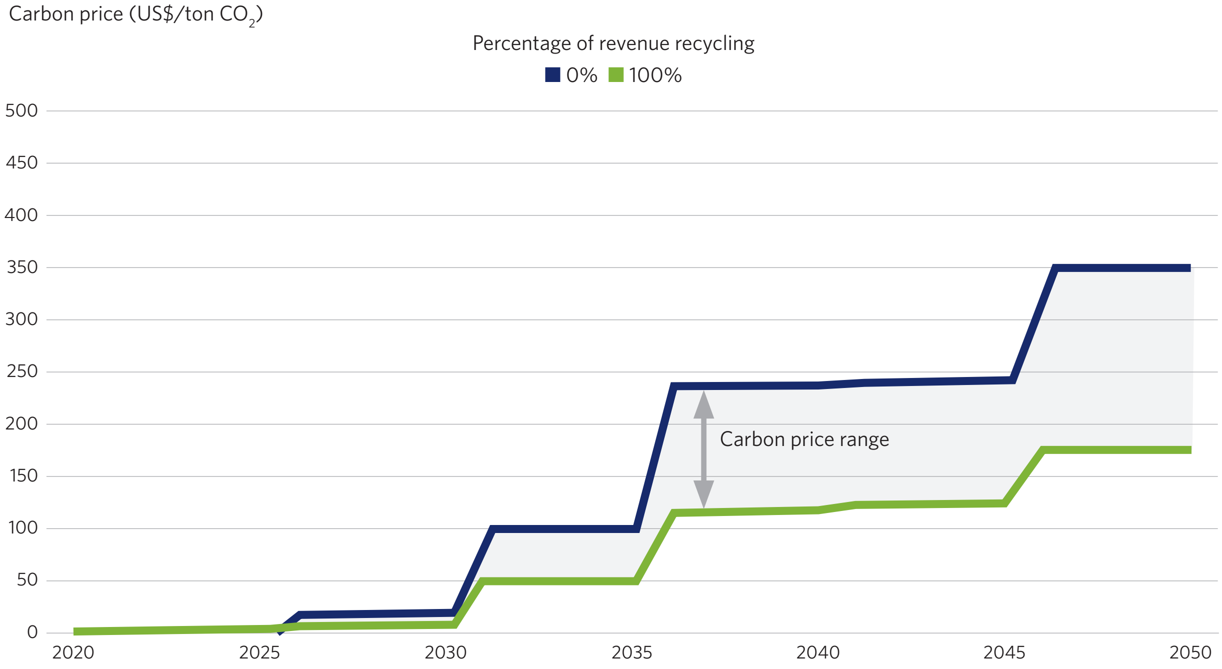
...and then follow it up with a global ban on fossil fueled vessels once the majority of the fleet has transitioned to alternative fuels.




1. This setup also addresses other key abatement considerations such as the need for the carbon price to be increased over time to reflect the growing damage expected from climate change, and sending a message to polluters that they must do more to reduce emissions.
2. How best to tackle disproportionate negative impacts is currently one of the most disputed topics surrounding carbon pricing. Recent discussions have specifically targeted questions about to create a level playing field for the maritime industry, and in what way any CO2-eq. levy should be measured and compensated for, e.g. how differences in socio-economic progress, remoteness to main markets and transport dependency should be considered when forming emission pricing schemes.

Source: Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2021

**Figure 21. Estimated Carbon Prices to Completely Decarbonize Shipping by 2050 (UMAS 2021 estimates)**




Source: UMAS 2021

An alternative way to deploy a carbon levy is through an earmark and return scheme. Under an earmark and return scheme, authorities use part of the revenues collected from the carbon tax to compensate early adopters of low carbon marine fuels. This compensation incentivizes shipping companies to adopt net zero carbon marine fuels by bridging the cost gap between fossil and low carbon and net carbon neutral alternatives. At the same time, the carbon tax penalizes the use of high carbon marine fuels.

Under the earmark and return scheme, a carbon price between $50 and $100 per $tCO_2$-eq would enable a transition to net carbon neutral shipping by 2050.

An earmark and return scheme should provide a clear and predictable carbon pricing trajectory, with a few scheduled price hikes, to enable the industry to adapt. Additionally, it should be deployed alongside regulatory measures, such as a global ban, that put an end-date to fossil fuel use in shipping. This would create a level playing field and avoid a relapse back to fossil fuels.

Another study by the University Maritime Advisory Service (UMAS) for the Getting to Zero Coalition estimates that an average carbon price of $191 per ton of $CO_2$, starting in 2025, would enable full decarbonization by 2050. An average price of just $96 per ton of $CO_2$ would have the same effect if 100 percent of the revenue was fed back to the industry to aid the decarbonization effort. The study points out that the real price will probably fall somewhere in between, given that some of the revenues should be spent in ensuring a more equitable transition. The study also points out that scheduled price hikes suggested in this study could be difficult to implement for political reasons[25] (See Figure 21).

25 Baresic, D., Rojon, I., Shaw, A., & Rehmatulla, N. (2022). Closing the Gap: An Overview of the Policy Options to Close the Competitiveness Gap and Enable an Equitable Zero-Emission Fuel in Shipping. London: University Maritime Advisory Service (UMAS). Retrieved June 7, 2022 from https://www.u-mas.co.uk/wp-content/uploads/2022/01/Closing-the-Gap_Getting-to-Zero-Coalition-report.pdf

# 3. Marine Methanol Fuel – Performance and Costs

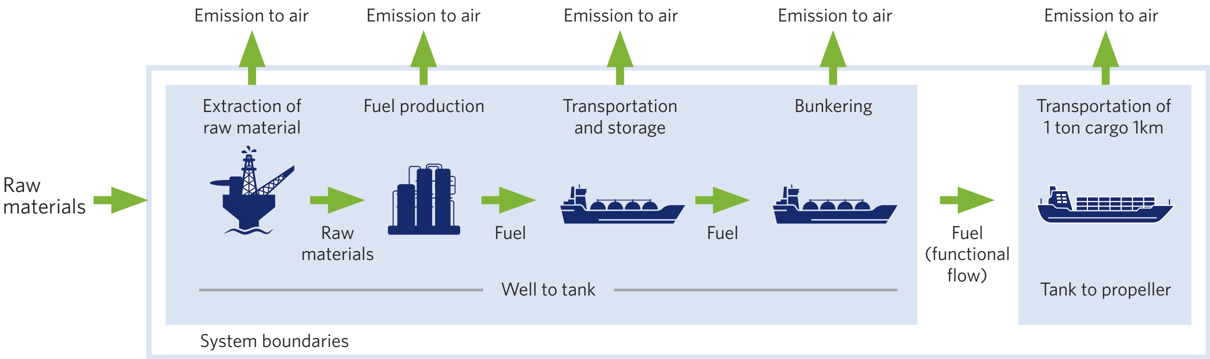
As seen in chapter 2, regulations aimed at curbing GHG emissions in shipping are set to become gradually more stringent as the industry transitions to net carbon neutral emissions between now and the second half of the century. This transition requires ship operators to maximize operational efficiency, adopt low carbon fuels, and deploy new technologies. The future of shipping looks complex, as regulation and pressure from stakeholders such as cargo owners drive operators to adopt a diverse fuel mix along with ongoing technical improvements.

This chapter shows how marine methanol fuel can help vessel owners navigate the transition to net carbon neutral shipping.

## 3.1. Reducing GHG and Pollutant Emissions in Shipping with Marine Methanol

Most are aware that fuel combustion generates emissions. However, the emissions generated during extraction, processing, and distribution are often overlooked. Considering emissions at every step of a fuel's lifecycle is essential to obtain a full picture of the climate change impact of each fuel. This approach to assessing emissions is referred to as well-to-propeller or well-to-wake.

**Figure 22. Lifecycle Emissions in Shipping from Well-to-Propeller**




Source: Methanol Institute

The IMO is currently working on a Life Cycle Analysis Guidelines for marine fuels aiming at covering fuel emissions from a well-to-wake basis[26]; ship operators must consider this fact when planning their fuel strategies.

Additionally, $CO_2$ is not the only greenhouse gas emitted in this process. Depending on the feedstock and fuel utilization method, methane ($CH_4$) and nitrous oxide ($N_2O$) may also be emitted[27]. For this reason, the impact of different GHG is normalized considering global warming potential (GWP) over a 100-year period and expressed in grams of $CO_2$-equivalent (see Figure 23)

26 International Maritime Organization (IMO). (2022, May 24). ISWG-GHG 12: Reducing GHG Emissions from Ships. Retrieved June 12, 2022 from imo.org: https://www.imo.org/en/MediaCentre/PressBriefings/pages/ISWGHGMay2022.aspx

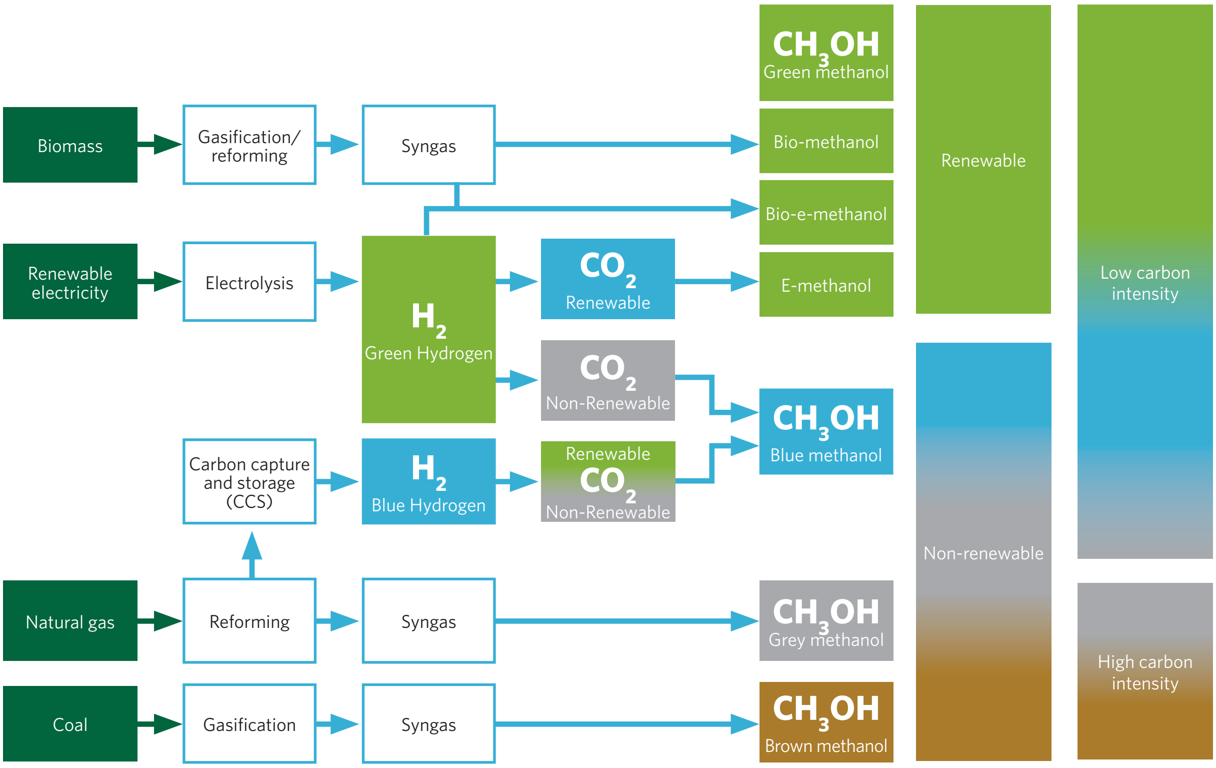
27 Campbell, M., Davies, A., MacLean, G., Martin, C., Raugei, M., & Scammell, H. (2021). Report for the Study on Sustainability Criteria and Life Cycle GHG Emission Assessment Methods and Standards for Alternative Marine Fuels. Ricardo Energy & Environment. Retrieved June 12, 2022, from https://greenvoyage2050.imo.org/wp-content/uploads/2022/01/RicardoED_IMOAlternativeFuels_ReportFinal.pdf

## Figure 23. Global Warming Potential of Methane ($CH_4$) and Nitrous Oxide ($N_2O$)

| Emissions | Global warming potential for a 100-year time horizon (g $CO_2$ equivalent/g emissions) |
|---|---|
| $CO_2$ | 1 |
| $CH_4$ | 25 |
| $N_2O$ | 298 |

Source: Forster 2007

## Figure 24. Methanol Production Pathways




Source: IRENA and Methanol Institute, 2021

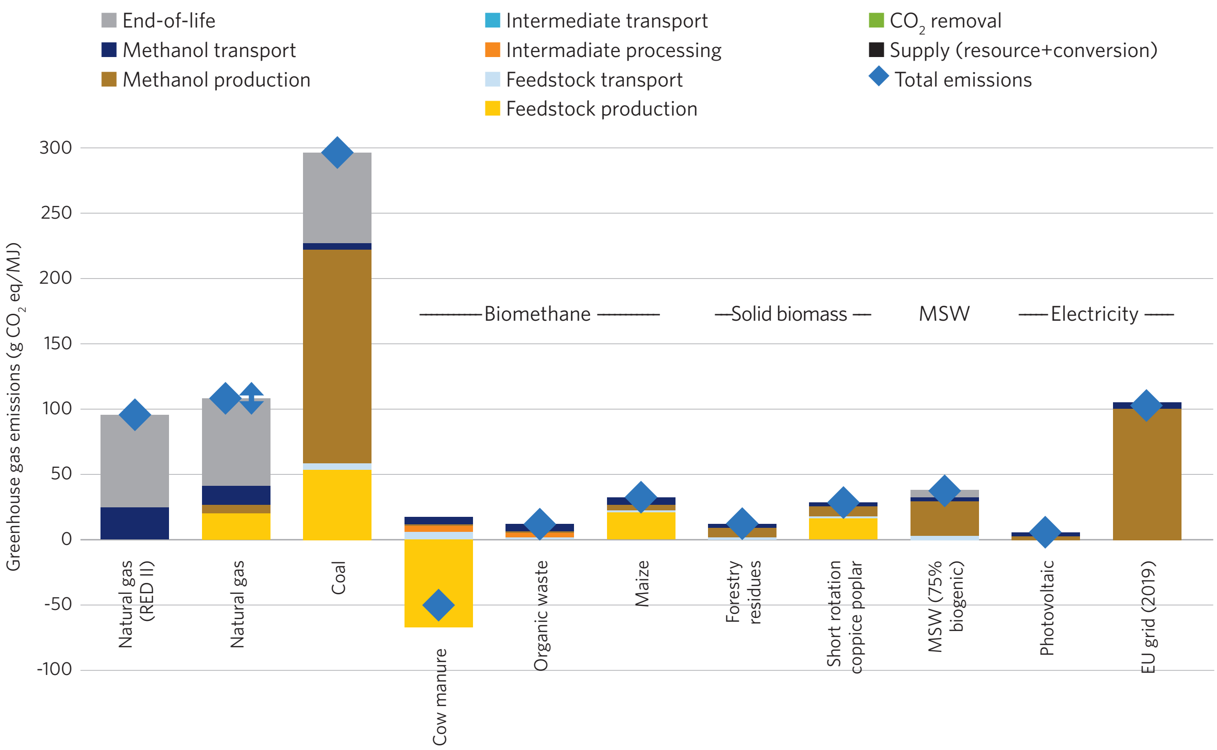
Methanol can be produced from biomass, bio-methane, renewable electricity/green hydrogen plus $CO_2$, and from fossil sources such as natural gas and coal. The carbon intensity of methanol varies depending on the feedstock and the production pathway deployed (See Figure 24).

Most methanol is currently produced from natural gas, where natural gas is used both as a feedstock and as a process fuel. $CO_2$ emissions from the facility are accounted for by using a carbon mass balance methodology. Modern facilities today produce methanol with an estimated carbon footprint of about 110 $gCO_2eq/MJ$, which is higher than what was considered state-of-the art two decades ago (about 97 $gCO_2eq/MJ$), most likely because the insight in carbon accounting has improved with more current data[28, 29].

28 This discussion on the carbon content of methanol comes from the following report prepared for the Methanol Institute: Hamelinck, C., & Bunse, M. (2022, February 4). The carbon footprint of methanol produced from various feedstocks. Retrieved June 12, 2022, from Studio Gear Up: https://www.studiogearup.com/the-carbon-footprint-of-methanol-produced-from-various-feedstocks.

29 Other authoritative models, such as the ICCT and GREET have arrived at different conclusions regarding the carbon intensity of gray methanol. Sometimes these figures are lower than the stated 110 $gCO_2eq$, depending on the assumptions used in the calculation.

**Figure 25. Carbon Footprint of Methanol Pathways (Well-to-Wake in $gCO_2eq/MJ$)**




Source: Hamelinck & Bunse, 2022

The footprint is especially sensitive to the source of the natural gas. When sourced from the less carbon emitting sources of natural gas, the methanol supply chain emissions can decrease to about 103 $gCO_2eq/MJ$. When exhaust $CO_2$ is recycled back to the methanol reactor, the production of methanol increases and facility emissions decrease, and as a result the lifecycle emissions per MJ of product decreases to 93-101 g $CO_2eq/MJ$. These results are between 4 $gCO_2eq/MJ$ better and 13 $CO_2eq/MJ$ higher than the value used in calculations by EU Joint Research Centre JRC under RED II[30].

Production from coal only takes place in China and has a higher carbon footprint of nearly 300 $gCO_2eq/MJ$, due to large emissions associated with both the mining of coal and the methanol conversion process.

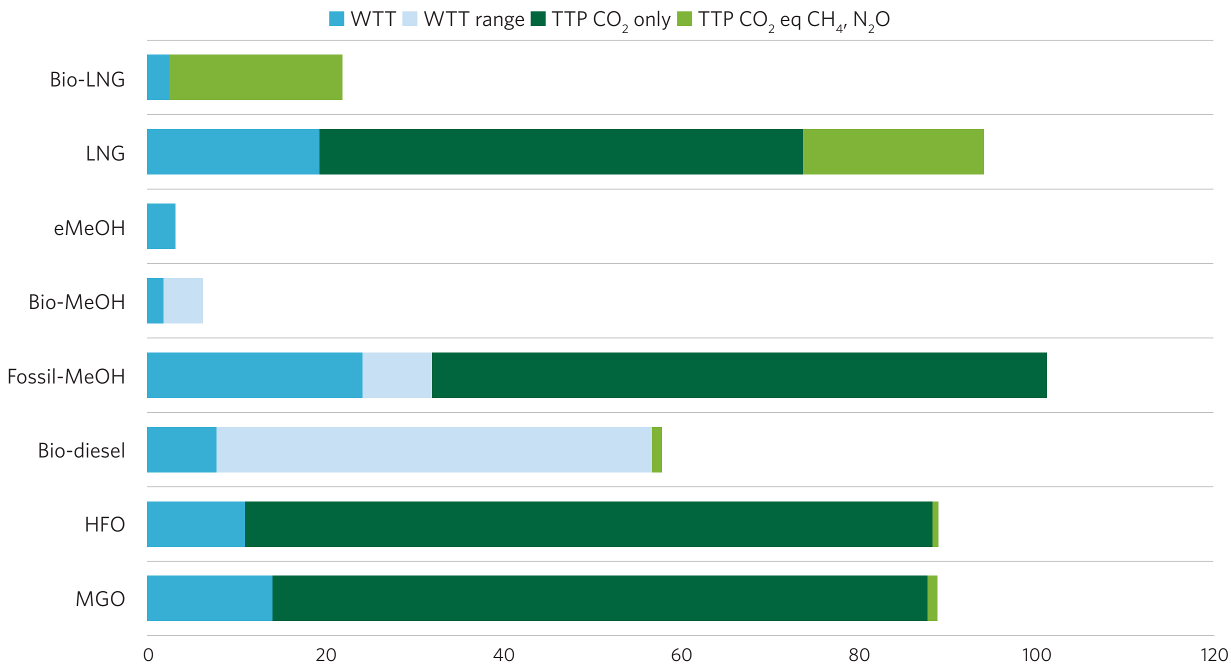
Production from renewable sources, such as from biomethane, solid biomass, municipal solid waste (or MSW, which contains a considerable fraction of organic waste), and renewable energy, has a low carbon footprint. Most of these pathways achieve 10-40 g $CO_2$ eq/MJ, and some pathways even have negative emissions (-55 $gCO_2$ eq/MJ for methanol from biomethane from cow manure) which means effectively that $CO_2$ is removed from the atmosphere or that the pathway avoids emissions that would have otherwise taken place in other processes.

Once well-to-propeller emissions are considered, bio-methanol and renewable e-methanol are among the lowest emission shipping fuels.

Regarding pollutant emissions, as seen in Chapter 2, regulations are mainly concerned with limiting $SO_X$ and $NO_X$ emissions.

30 Joint Research Centre - European Commission (2017, July) Definition of input data to assess GHG default emissions from biofuels in EU legislation – Version 1 C. Retrieved on September 15, 2022 from https://op.europa.eu/en/publication-detail/-/publication/f95536ce-6cf8-11e7-b2f2-01aa75ed71a1/language-en

## Figure 26. Well-to-Propeller Emissions of Different Fuels (gCO2eq/MJ)




Note: WTT: Well-to-Tank; TTP: Tank-to-Propeller Source: Green Marine Methanol Consortium

## Figure 27. Pollutant emissions from HFO, MGO, Methanol and LNG (g/kWh, tank-to-propeller)

| g/kWh | HFO 0.5% S | MGO 0.1% s Tier II | MGO 0.1% s Tier III | Methanol Tier II | Methanol Tier III | LNG Tier III |
|---|---|---|---|---|---|---|
| $NO_X$ | 12.8 | 9 | 2-3 | 5 | 2.2 | 2 |
| $SO_X$ | 2.0 | 0.36 | 0.36 | 0.007 | 0.007 | 0.009 |
| $PM_{10}$ | 0.74 | 0.23 | 0.23 | 0.034 | 0.034 | 0.02 |

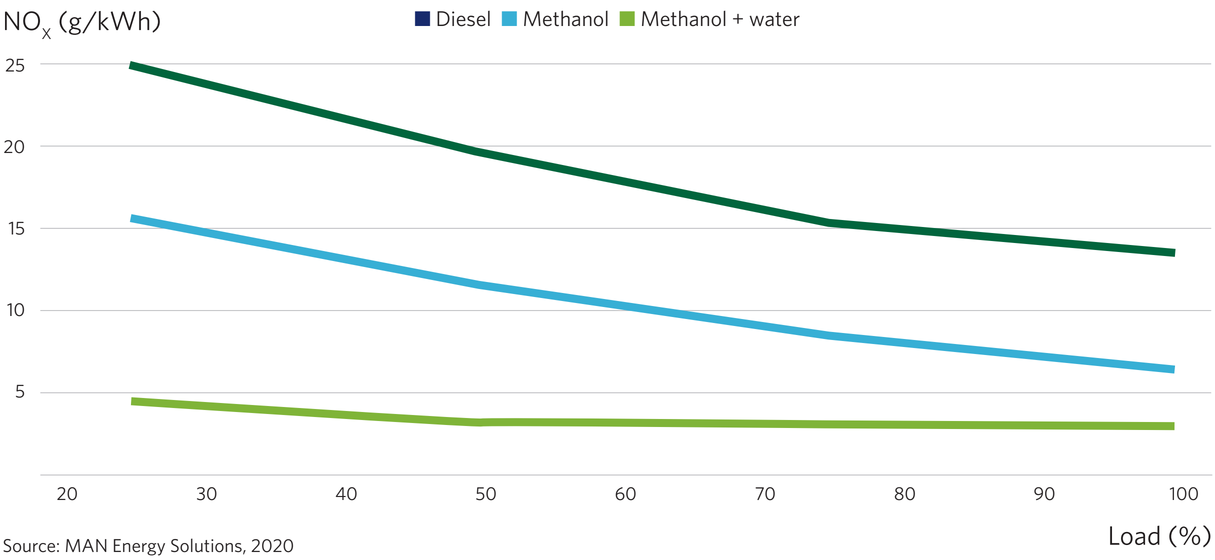
Source: Green Maritime Methanol, 2021

Using methanol in ships emits very little $SO_X$, as the methanol molecule ($CH_3OH$) contains no sulfur. What little $SO_X$ emissions occur come from the diesel employed as pilot fuel in dual fuel engines, not the methanol itself. Marine methanol fuel comfortably meets IMO's regulations on $SO_X$ emissions.

$NO_X$ emissions from methanol are much lower than those that result from the combustion of HFO or Marine Gas Oil (MGO). However, methanol still falls short of Tier 3 $NO_X$ emission standards unless it is mixed with water during the combustion process. According to MAN Energy Solutions, operators can reduce $NO_X$ emission to Tier 3 levels by deploying a mixture of methanol, 25 to 40 percent of water, and 3 to 5 percent of diesel as a pilot fuel[31]. It is worth noting that the methanol molecule does not contain nitrogen; rather $NO_X$ comes from the reaction of nitrogen and oxygen at high temperatures. Mixing methanol with water reduces the combustion temperature, thereby limiting the formation of $NO_X$.

31 MAN Energy Solutions. (2020, March 30). Market Update Note: Introducing the LGIM-W principle. Retrieved June 12, 2022, from https://man-es.com/docs/default-source/marine/tools/introducing-the-lgim-w-principle.pdf?sfvrsn=a128e177_8

**Figure 28. Methanol plus Water - $NO_x$ Reduction as a Function of Load**



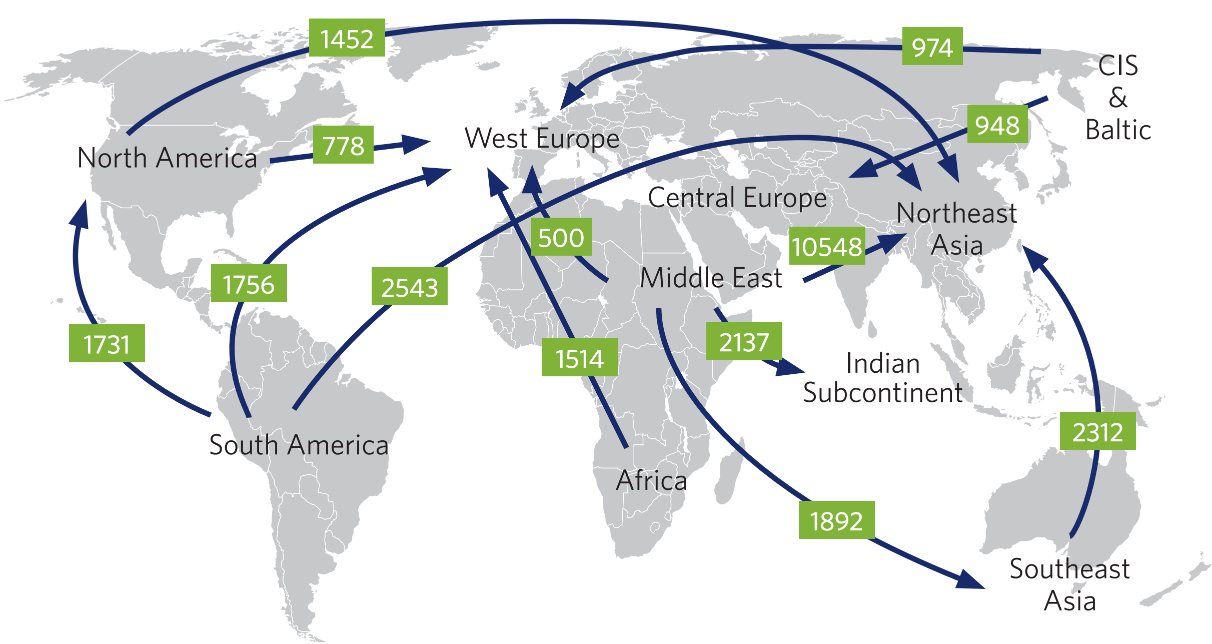

Source: MAN Energy Solutions, 2020

Methanol also produces very low PM emissions, and here too, the small amount of PM emissions that are produced come entirely from the diesel used as pilot fuel. It is commonly known that methanol burns with an invisible flame, this is because the methanol molecule contains no carbon-to-carbon bonds which produce soot or particulate matter. This is important because PM, produced in the combustion of fuels such as diesel, poses a significant danger to health.

## 3.2. Methanol Availability

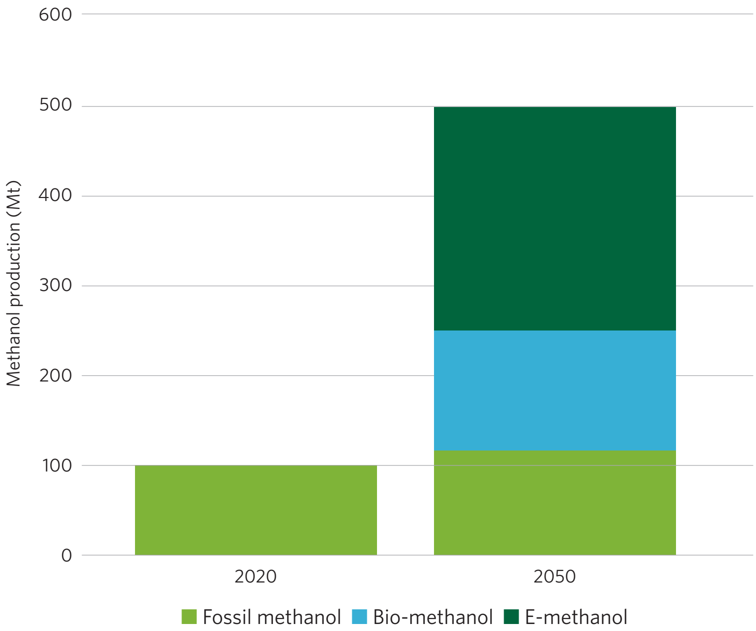
Ship operators who run methanol fleets would be able to procure methanol with relative ease. Methanol is available at over 120 ports worldwide and shipped globally. Today, there are more than

**Figure 29. Main Methanol Interregional Trade Flows (Thousand metric tons per annum)**




Source: Chemical Market Analytics

**Figure 30. Methanol Production by 2050**




Source: IRENA

90 methanol production facilities all over the world, with annual supply of nearly 100 million tons of methanol (33 billion gallons or 125 billion liters)[32].

Currently, most globally traded methanol is produced from the steam reformation of natural gas – so-called gray methanol – in plants that can produce up to 5,000 tons per day, or 1.8 million tons per year. Conventional natural gas-based plants can reduce their carbon footprint by recirculating $CO_2$, bringing in $CO_2$ over the fence, adding green hydrogen, or replacing natural gas-driven process equipment with electrically driven equipment to produce low carbon or "blue" methanol.

According to the International Renewable Energy Agency (IRENA), by 2050 e-methanol and bio-methanol – "green" methanol – are expected to make up about 80 percent of total production, which could reach 500 million tons per year[33]. As discussed in the next section, the availability of feedstocks for bio-methanol and e-methanol production are likely to limit most individual production facilities to capacities ranging from 50,000-250,000 tons per year. Whether produced from gray, blue or green feedstocks, the methanol molecule will have the same physical properties, facilitating the transition of marine methanol over time as more low carbon and net carbon neutral methanol enters the global supply chain.

## Feedstock availability

Whether bio-methanol and e-methanol production can expand to support the decarbonization of shipping depends on the raw materials being available in sufficient quantities and at a reasonable price at the point of production. In the case of e-methanol, the relevant feedstocks are renewable $H_2$ and $CO_2$. Green hydrogen is produced from the electrolysis of water using renewable electricity from wind, solar, hydropower, or geothermal resources. The required $CO_2$ could be obtained from industrial flue gases, biogenic sources, or direct air capture (DAC). When it comes to bio-methanol,

32 The Methanol Industry. (2022). Retrieved May 2, 2022, from Methanol Institute: https://www.methanol.org/the-methanol-industry/

33 IRENA and Methanol Institute. (2021). Innovation Outlook: Renewable Methanol, Abu Dhabi: International Renewable Energy Agency. Retrieved November 19, 2022, from https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol

the feedstocks include a variety of biogenic matter such as agricultural and forestry residues, biogas and biomethane, manure, municipal solid waste, and black liquor from pulp and paper mills.

Let's start by considering the availability of biogenic feedstocks for bio-methanol.

### Availability of Feedstocks for Bio-Methanol

The first aspect to consider when assessing feedstock availability is what types of feedstocks are classified as sustainable. In general terms, legislation considers biogenic feedstocks sustainable when they do not compete with food crops. Corn, for example, is not considered a sustainable biofuel feedstock in many regions. Additionally, the crop must not lead to additional emissions, which rules out traditional uses of biomass.

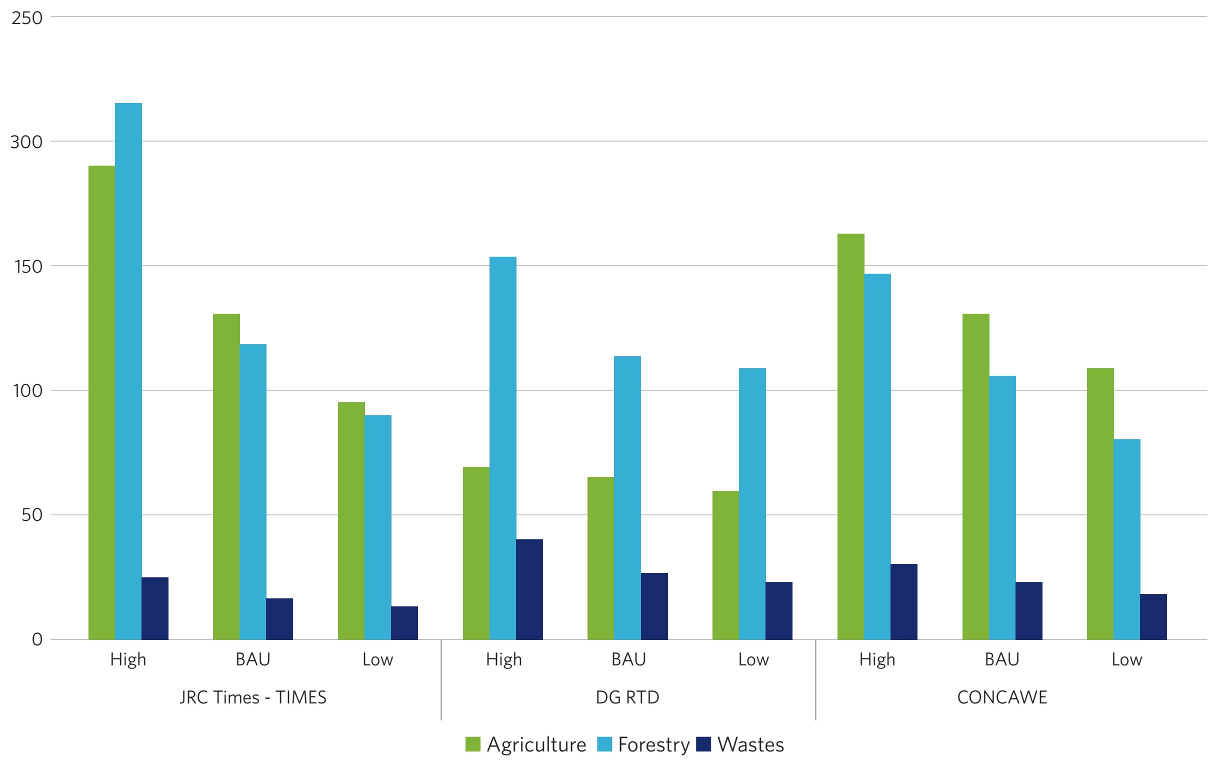
A meta-analysis of three papers on feedstock availability for biofuels in the EU has reached the conclusion that feedstock availability is not the main barrier to the uptake of alternative fuels[34]. Notice, however, how estimated availability varies in each of the three studies assessed (see Figure 31). This is mainly because different feedstocks are considered in each study (see Figure 32).

Beyond Europe, estimates of global biomass availability vary significantly, as can be seen in Figure 33. According to ICCT estimates (the most conservative) by 2050 biomass supply will stand at 2150 Mtoe per year, which is not enough to decarbonize all sectors[35]. However, other sources claim that

34 Prussi, M.; Panoutsou, C; Chiaramonti, D. (2022) Assessment of the Feedstock Availability for Covering EU Alternative Fuels Demand. Applied Sciences, 12, 740. https://doi.org/10.3390/app12020740

35 Concawe (2019). A look into the maximum potential availability and demand for low carbon feedstocks/fuels in Europe 2020-2050 – literature review, Concawe Review, 27, 2

**Figure 31. Potential Feedstock Availability in Three Different Studies (Million tons of oil equivalent - Mtoe)**




Source: Prussi, Panoutsou, and Chiaramonti, 2022

**Figure 32. Feedstocks Considered in Three Studies on Feedstock Availability for Biofuels in the EU**

| | Agreecultural Feedstocks | Forest Feedstocks | Biowastes |
|---|---|---|---|
| JRC ENSPRESSO | Biofuel crops from rotational arable crops also used for food and feed purposes (e.g., oil seed rape, sunflower, wheat, maize, etc.); primary residues from arable crops (straw and stubbles), pruning, cutting and harvesting residues from permanent crops, dedicated perennial crops, energy maize and grassland cutting solid and liquid manure. | Stemwood for fuelwood, primary residues and secondary residues from wood processing industries (sawmill residues, which are generally converted into chips and pellets before they are sold on; saw dust; and black liquor). | Biomass fraction of municipal solid wastes (MSW)<br>Mixed wastes from food preparation (including utilized cooking oil)<br>Post-consumer wood<br>Sewage sludge. |
| DG RTG | Crop residues from arable crops (straw and stubbles) pruning, cutting and harvesting residues from permanant crops, dedicated energy crops (on below average quality land. Only the land that is released from other crops in a business-as-usual baseline has been used in the model for growing of energy crops). | Stemwood, primary residues (stem and crown biomass from early pre-commercial thinnings.<br>Logging residues from thinnings and final fellings; Stump extraction from final fellings and thinnings) and secondary residues from forest industries (sawmill residues, sawdust, black liquor). | Biomass fraction of municipal solid wastes (MSW)<br>Mixed wastes from food preparation (including utilized cooking oil)<br>Post-consumer wood<br>Sewage sludge. |
| Concawe | Agricultural residues (primary residues from arable crops (straw and stubbles), pruning, cutting and harvesting residues from permanent crops, dedicated perennial crops. | Stemwood, primary residues (Logging residues - see DG RTG definition and secondary residues from forest industries (Sawmill residues, sawdust), post-consumer wood. | Biomass fraction of municipal solid wastes (MSW).<br>Mixed wastes from food preparation (including utilized cooking oil)<br>Post-consumer wood<br>Sewage sludge. |

Source: Prussi, Panoutsou, and Chiaramonti, 2022, adapted from Concawe's Sustainable Biomass Availability in the EU study.

there should be enough biomass to support the decarbonization of shipping. In Europe alone, biomass supply should be able to support the production of up to 176 million tons of waste-based biofuels per year by 2050, without competing with food crops or causing harm to biodiversity[36].

Even though advanced biofuels will also be required to decarbonize sectors such as aviation and industrial process heat, these figures show that biomass is available to support large scale methanol production.

An additional consideration is that the infrastructure needs to be set up to gather and transport waste biomass to biofuels production centers at large scale and low cost. IRENA estimates the bio-methanol production could reach 135 million tons per year by 2050.

### Availability of Feedstocks for E-Methanol Production: Renewable $H_2$ and Sustainable $CO_2$

IRENA has estimated that e-methanol production could reach 250 million tons per year by 2050. This level of e-methanol production would require 350 million tons of $CO_2$ and 48 million tons of $H_2$[37]. To put this into perspective, current $H_2$ demand for all uses stands at approximately 90 million tons per year, out of which 12.7 million tons per year are dedicated to methanol production, according to 2021 figures (International Energy Agency, 2022) [38].

To produce renewable e-methanol, it is necessary to deploy $H_2$ that has been produced through electrolysis powered by low carbon energy. To understand whether enough renewable $H_2$ will be

36 Panoutsu, Calliope and Maniatis, Kyriakos (August 2021). Sustainable biomass available in the EU to 2050. Imperial College London Consultants for Concawe. Retrieved July 16 https://www.fuelseurope.eu/wp-content/uploads/Sustainable-Biomass-Availability-in-the-EU-Part-I-and-II-final-version.pdf

37 IRENA and Methanol Institute. (2021). Innovation Outlook: Renewable Methanol, Abu Dhabi: International Renewable Energy Agency. Retrieved November 19, 2022, from https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol

38 International Energy Agency. (2022, September). Hydrogen. Retrieved December 11, 2022 from iea.org: https://www.iea.org/reports/hydrogen

**Figure 33. Global Biomass Availability Estimates**

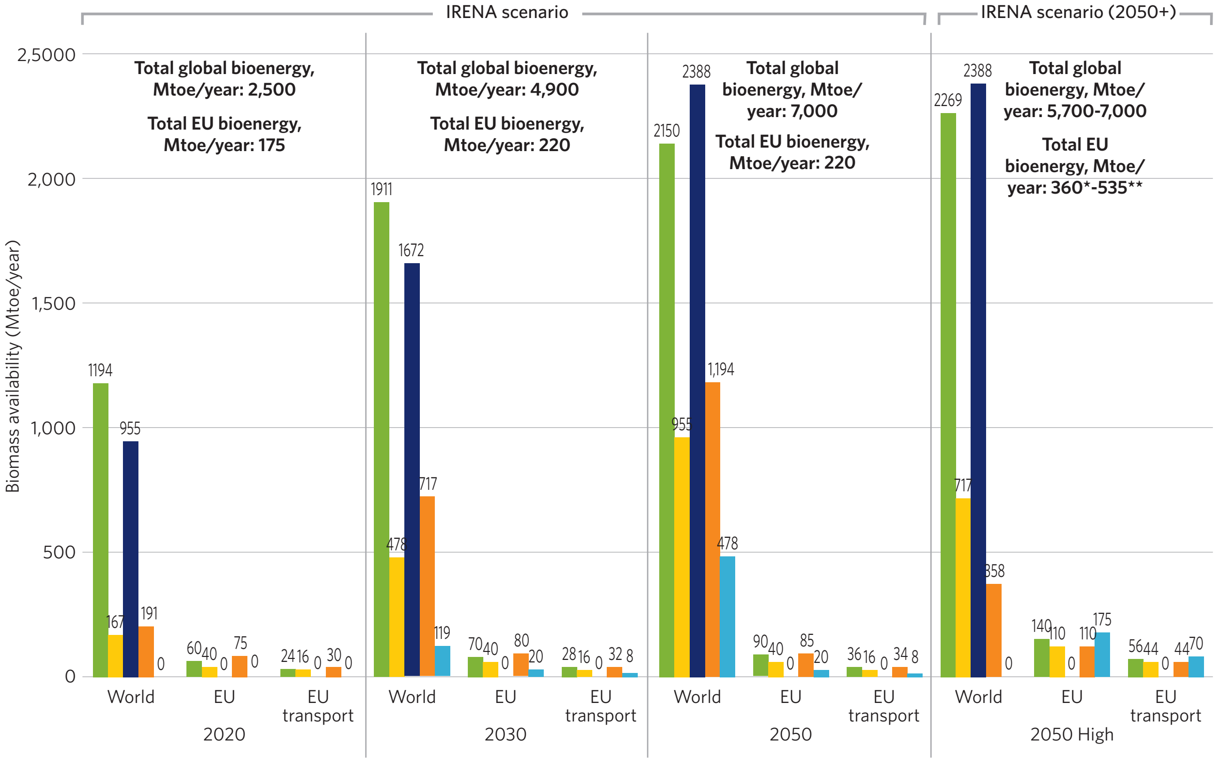



Figure 1 notes:
Energy contents: (1 toe=41,868 GJ)
Coversion factors used by Concawe for comparison purposes (simplified approach) are:

- Agriculture residues energy content: 0.56 toe/t
- Forestry energy content: 0.21 toe/t
- Waste energy content: 0.76 toe/t
- Aquatic (algae) energy content: 0.48 toe/t

* ICCT has the most conservative view, assuming that the maximum global biomass availability in 2050 is around 2,150 Mtoe/y
**biomass availability if the full potential for algae is realized

- Agriculture (non-food related)
- Forestry
- Energy plants
- Waste
- Aquatic (algae)

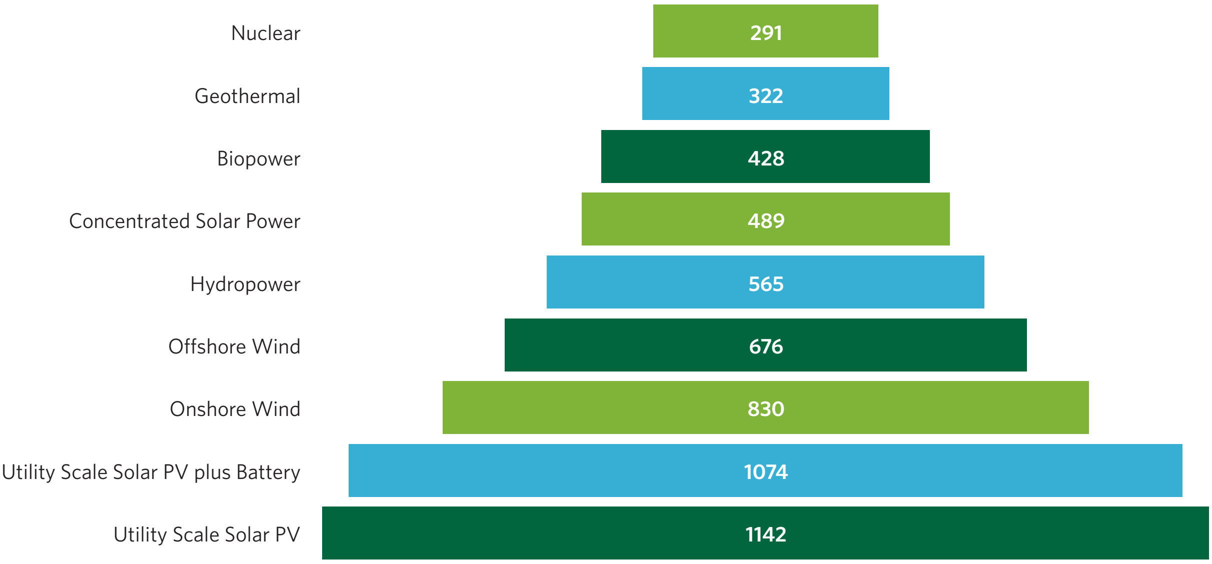
Source: Concawe

available to support renewable e-methanol production, it is important to consider the amount of renewable energy required to produce renewable $H_2$.

Going back to IRENA's renewable methanol production estimates, 250 million tons per year by 2050 requiring 48 million tons of renewable $H_2$, the same report estimates that 2400 TWh per year (8.6 EJ per year) of renewable electricity are needed to power the 280 GW of electrolyzers required to support this volume of hydrogen production, assuming the electrolyzers consume 50 MWh per ton of $H_2$. If renewable energy could power the electrolyzers without interruption, around 275 GW of dedicated renewable capacity would provide enough electricity. However, solar photovoltaic (PV) and wind power, the cheapest and most extended renewable energy technologies, do not produce electricity 24/7. Rather, PV produces electricity only when the sun shines and wind only when the wind blows. Therefore, PV and wind are known as variable renewables. For this reason, the report estimated that around 920 GW of PV or 500 GW of wind would be required to support the production of 48 million tons of renewable $H_2$, assuming capacity factors of 30 percent and 55 percent for PV and wind, respectively. The electricity required to power electrolyzers will come from a mix of technologies, some of which have higher capacity factors than PV and wind (see Figure 34).

Renewable $H_2$ production is still a fraction of total production, although it is ramping up fast. Countries with abundant renewable resources stand a better chance of achieving economies of scale

**Figure 34. Power Generation Capacity (GWe) Required to Produce 48 Million Tons of Renewable $H_2$ per Year**

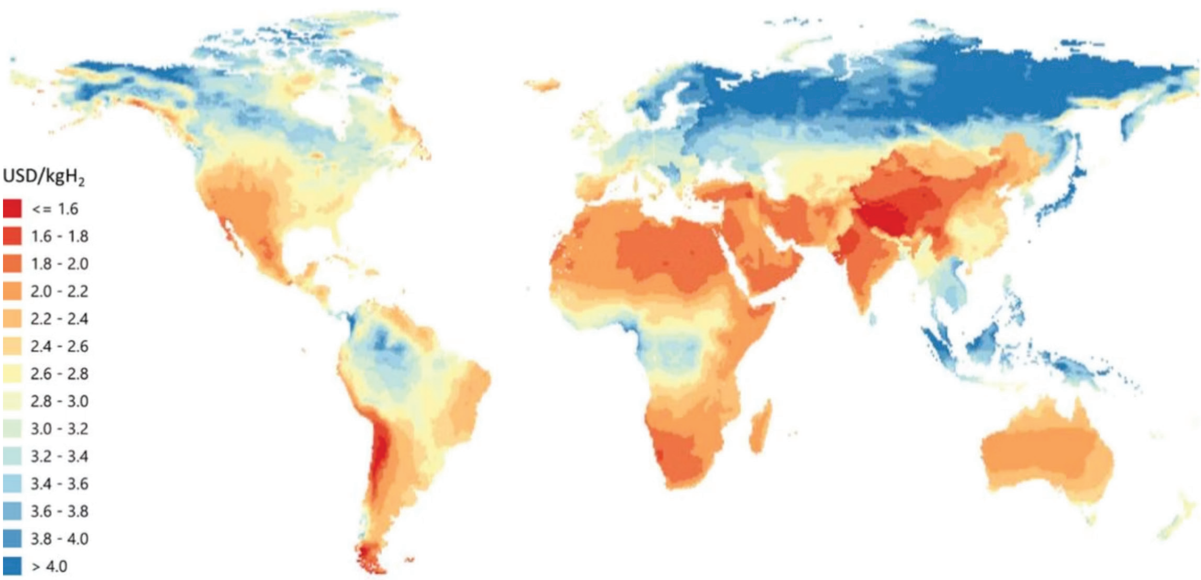



Notes: 48 million tons of renewable $H_2$ per year are required to meet the renewable methanol production target proposed by IRENA (250 million tons by 2050)
Calculations are based on average capacity factors published by NREL (2021): Biopower: 64 percent, Concentrated Solar Power (CSP): 56 percent, Geothermal: 85 percent, Hydropower: 49 percent, Nuclear: 94 percent, Offshore Wind: 41 percent, Onshore Wind: 33 percent, Utility Scale PV: 24 percent, Utility Scale PV plus Battery Storage: 26 percent.
Assuming an installed electrolyzer capacity of 280 GW and electrolyzer consumption of 50 MWh per ton of $H_2$ (IRENA).

and producing renewable $H_2$ at a competitive cost. Solar and wind are the two renewable energy technologies with the highest potential for scaling up fast.

In addition to $H_2$, $CO_2$ is also needed to produce methanol through the electrofuel pathway. In 2021, $CO_2$ emissions from energy combustion and industrial processes reached an all-time high of 36.3 Gt[39]. Capturing some of this $CO_2$ and upcycling it by mixing it with renewable $H_2$ to produce methanol

**Figure 35. Hydrogen Production Cost from Hybrid PV and Wind Power Systems in the Long Term**




Source: IEA

39 International Energy Agency. (2022, March). Global Energy Review: $CO_2$ Emissions in 2021. Retrieved November 19, 2022, from iea.org: https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2

### Figure 36. Technical Characteristics of Different Marine Fuels

| Fuel type | LHV* [MJ/kg] | Volumetric energy density [GJ/m³] | Storage pressure [bar] | Storage Temperature [°C] |
|---|---|---|---|---|
| MGO | 42.7 | 36.6 | 1 | 20 |
| LNG | 50 | 23.4 | 1 | -162 |
| Methanol | 19.9 | 15.8 | 1 | 20 |
| Liquid ammonia | 18.6 | 12.7 | 1/10 | -34/20 |
| Liquid hydrogen | 120 | 8.5 | 1 | -253 |
| Compressed hydrogen | 120 | 7.5 | 700 | 20 |

*LHV: Lower heating value. Based on De Vries (2019)
Source: IRENA

would essentially reuse this $CO_2$ to produce net carbon neutral methanol without adding new $CO_2$ to the atmosphere. This $CO_2$ can come from other sources, such as the combustion of biomass with carbon capture and storage (BECCS) or through direct air capture (DAC). Currently there are 19 DAC facilities capturing around 0.01 million tons of $CO_2$ annually. Although nascent, the IEA estimates that DAC is poised to scale up fast to reach 85 million tons of $CO_2$ per annum by 2030[40]. Carbon capture from industrial activity is also a source of $CO_2$ for methanol production and one of the most viable means to drastically reduce emissions from heavy industries such as cement, chemicals and steel. By 2070, the IEA estimates that carbon capture will account for up to two thirds of emissions reductions in heavy industry.[41]

## 3.3. Energy Density of Methanol and Implications for Shipping

Methanol, also known as methyl alcohol, remains liquid at ambient temperature and pressure. This makes transporting, storing and bunkering methanol significantly cheaper and easier than fuels such as ammonia, hydrogen, or LNG.

However, the energy density of methanol is lower than that of traditional shipping fuels. For example, MGO has an energy density of 36.6 GJ/m³ compared to methanol's 15.8 GJ/m³.This means that on a methanol-powered ship, storage and fuel tanks take about 2.4 times more space than on ship than runs on MGO. This disadvantage is partially mitigated by the fact that methanol can be stored in conventional fuel storage tanks and even ballast tanks on-board a vessel, unlike fuels such as LNG and $H_2$ that require cryogenic storage[42].

Methanol has a higher energy density than other potential fuels including LNG, ammonia, and hydrogen, particularly when considering the size of storage tanks, secondary barriers, and cofferdams[43].

Energy density helps determine the type of vessel and shipping application that methanol could best serve. The sweet spot for methanol appears to be with vessels that do not undertake very long or short journeys and tend to sail to fixed, round-trip schedules. This includes cruise ships, inland waterway bulk transport vessels, short-sea container ships, ferries, shortsea tankers, deep sea container vessels

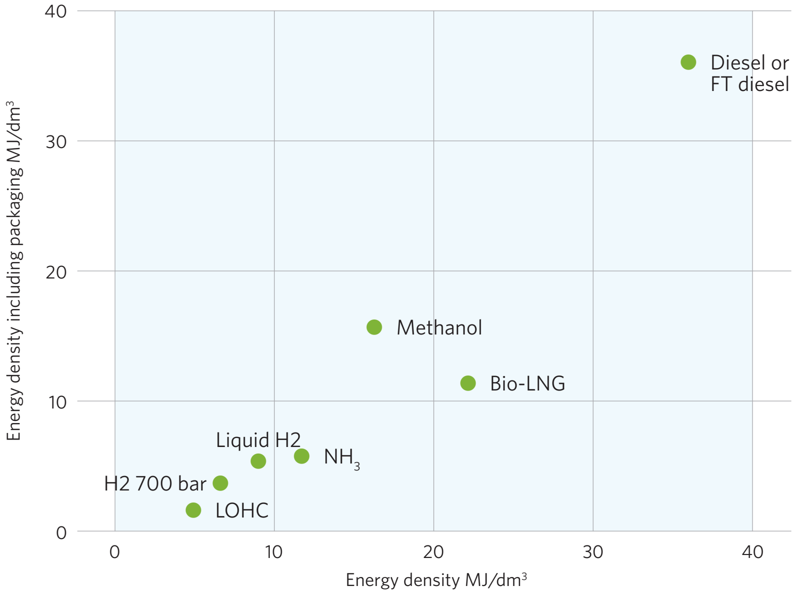
40 International Energy Agency. (2022, September). Direct Air Capture. Retrieved November 19, 2022, from iea.org: https://www.iea.org/reports/direct-air-capture

41 International Energy Agency. (2021, April). About CCUS. Retrieved March 15, 2023, from iea.org: https://www.iea.org/reports/about-ccus

42 IRENA. (2021). A pathway to decarbonise the shipping sector by 2050. Abu Dhabi: International Renewable Energy Agency. Retrieved November 19, 2022, from https://irena.org/publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050

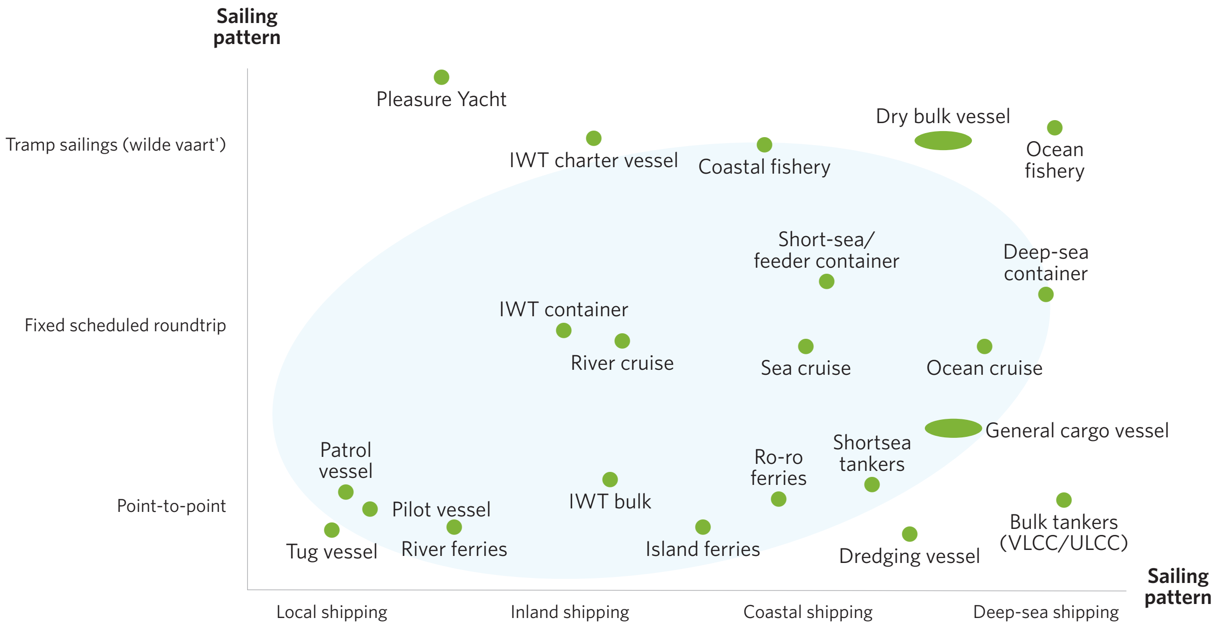
43 Green Maritime Methanol. (2021, February 19). Green Maritime Methanol - Towards a Zero Emission Shipping Industry. Retrieved June 12, 2022, from Green Maritime Methanol: http://resolver.tudelft.nl/uuid:0542ccdc-00fc-4229-a39f-401688d3ee03

## Figure 37. Energy Density of Different Fuel Types




Source: Green Maritime Methanol, 2021

## Figure 38. Heatmap of Methanol Shipping Applications




Source: Green Maritime Methanol, 2021

and general cargo vessels, according to research by TNO[44]. Although only 20 percent of the vessels are engaged in deep sea shipping, they make up 80 percent of bunker fuel demand.

TNO's analysis, based on sailing patterns and journey distances of vessels in the ports of Rotterdam and Amsterdam, does not consider the economic viability of methanol in different vessel types. It does, however, indicate that a wide range of vessels could be powered by methanol.
In particular, the research notes that in most mid-range shipping markets vessels already have over-

44 Zomer, G., Finner, S., Harmsen, J., Vredeveldt, L., & van Lieshout, P. (2020). Green Maritime Methanol: Operation aspects and the fuel supply chain. The Hague: TNO. Retrieved November 19, 2022, from https://publications.tno.nl/publication/34637282/W1qAIG/TNO-2020-R11105.pdf

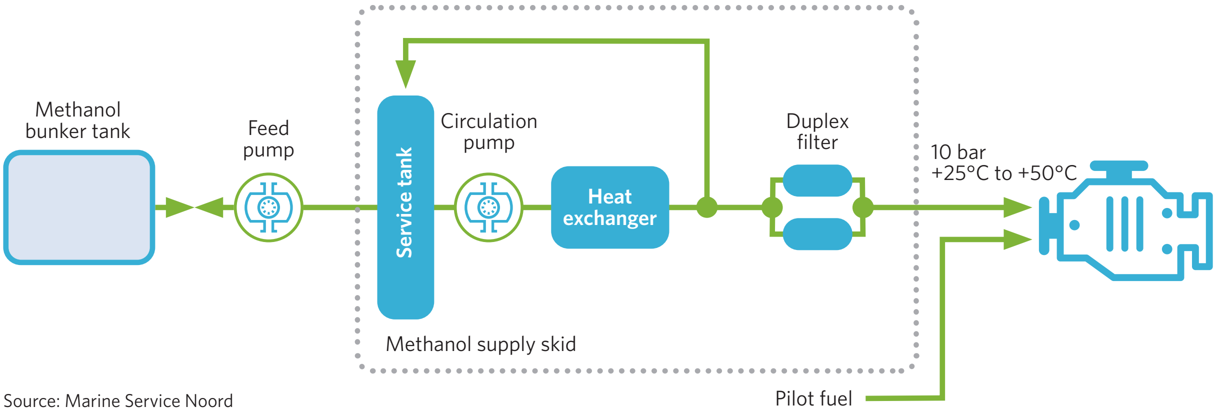
dimensioned tanks, which could facilitate the use of methanol in place of HFO or MGO. Furthermore, this could potentially be achieved without adjusting bunkering frequency, sailing patterns, or vessel designs.

## 3.4. Engines and Fuel Systems

Several companies have developed methanol-ready shipping engines and supply systems. Methanol internal combustion engines (ICE) have a high level of technological readiness and are available commercially. Fuel cells that run on methanol in a marine environment are currently under development with pilot demonstrations taking place around the world.

A list of methanol fueled vessels, either in operation or in the order books, can be found here: Methanol Vessels on the Water and on the Way. This document is updated regularly.

**Figure 39. Low-Pressure Methanol Fuel Supply Skid Diagram**




Source: Marine Service Noord

### Low and High-Pressure Methanol Supply Systems

Companies such as Anglo Belgian Corporation NV, MAN Energy Solutions, Rolls-Royce-owned mtu Solutions, Caterpillar, China State Ship Building, and Hyundai Heavy Industries have developed a low-pressure system that involves injecting methanol into the engine at around 10 bar and between 25ºC and 50ºC (see Figure 39).[45] In the case of MAN Energy Solutions, the fuel supply system operates at fairly low pressure (approximately 10 bar) in order to move the fuel from tank to engine room, where it is prepped (pre-heated in some cases to 50 °C for optimized combustion) before entering MAN's proprietary Fuel Booster Injection Valve (FBIV) at up to 300 bar[46].

Wärtsilä and others, meanwhile, use a high-pressure injection method where methanol enters the engine at around 400 bar (see Figure 40). This allows water to be mixed with the fuel to provide a methanol-aqueous solution, reducing costs and emissions.

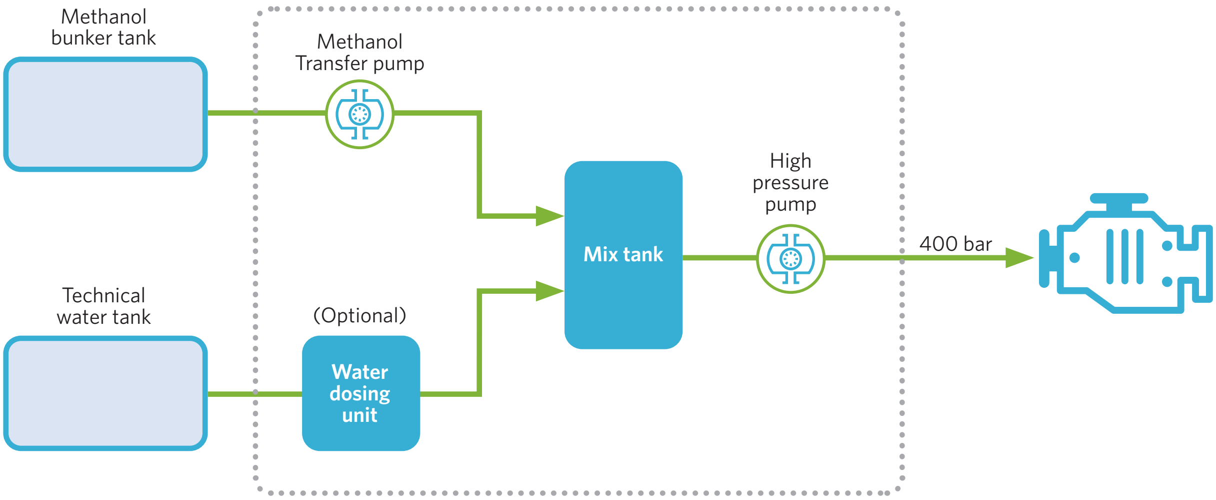
This configuration has already been proposed for a general cargo vessel called the MV Eemsborg, equipped with a 4.5 MW Wärtsilä engine.[47]

45 Marine Service Noord. (n.d.). Two concepts for methanol fuel systems. Retrieved November 19, 2022, from Marine Service Noord: https://marine-service-noord.com/en/products/alternative-fuels-and-technologies/methanol/two-concepts-for-methanol-fuel-systems/

46 MAN Diesel & Turbo (2014). Using Methanol Fuel in the MAN B&W ME-LGI Series. Retrieved April 7, 2023 from MAN Diesel & Turbo: https://www.mandieselturbo.com/docs/default-source/shopwaredocuments/using-methanol-fuel-in-the-man-b-w-me-lgi-series.pdf

47 Marine Service Noord. (n.d.). Case study MV Eemsborg. Retrieved November 19, 2022, from Marine Service Noord: https://marine-service-noord.com/en/products/alternative-fuels-and-technologies/methanol/case-study-mv-eemsborg/

**Figure 40. High-Pressure Methanol Fuel Supply Skid Diagram**




Source: Marine Service Noord

## Maritime Methanol Engines

Vessel engine manufacturers such as MAN Energy Solutions are already commercializing dual-fuel, methanol-ready two-stroke engines, some of which have been operating since 2016. MAN Energy Solutions now has 82 methanol dual-fuel engines in their order books, with another 120 orders being developed. For these dual-fuel engines, no modifications are needed inside the engine to run on methanol, the modifications are all in the injectors, cylinder heads, and the fuel delivery system.

MAN Energy Solutions is also due to start offering methanol retrofits for four-stroke engines from 2024, having overcome challenges relating to fuel system and injection technology. The company sees methanol four-stroke engines being used in container ships, ferries, fishing boats, and cruise ships,[48] while two-stroke dual fuel engines are said to be ideal for tankers carrying methanol, container ships, and potentially for other ship applications.

The commercial availability of methanol-burning two-stroke and four-stroke engines is important because both are widely used in shipping. Two-stroke engines are about 1.8 times more powerful than four-strokes for a given weight and can use low-grade fuel with greater efficiency and less maintenance, which reduces running costs.[49]

Two-stroke engines held a 54.3 percent share of the marine engine market in 2020 [50]. However, four-stroke engines were forecast to see higher growth up to 2028, on account of offering lower noise levels, higher speeds, and lower capital cost. It is unclear how this outlook may have been affected by recent rises in bunker fuel pricing, although increases in scrubber adoption[51], aimed at enabling vessels to use lower-cost fuels, suggest there could be a continuing trend towards two-stroke engine adoption.

48 MAN Energy Solutions. (2022). Methanol for the maritime energy transition. Retrieved November 19, 2022, from MAN Energy Solutions: https://www.man-es.com/marine/strategic-expertise/future-fuels/methanol

49 Wankhede, A. (2021, April 2021). Why 2-stroke Engines are Used More commonly than 4-stroke on Ships? Retrieved November 19, 2022, from Marine Insight: https://www.marineinsight.com/main-engine/why-2-stroke-engines-are-used-more-commonly-than-4-stroke-on-ships/

50 GreyViews. (2022, Jan). Global Marine Engines Market Overview. Retrieved November 19, 2022, from greyviews.com: https://greyviews.com/reports/global-marine-engines-market/17

51 Grainger, T. (n.d.). Shipping companies are taking a new look at scrubbers. Retrieved November 19, 2022, from Pacific Green: https://www.pacificgreen-group.com/articles/shipping-companies-are-taking-new-look-scrubbers/

## Figure 41. Methanol Engine Manufacturers

| | |
|---|---|
| **Anglo Belgian Corporation (ABC)** | DZC dual-fuel engine portfolio, with 6 and 8 cylinder inline engines and 12 and 16 cylinder V-engines, covers a power range from 600 kW up to 10.4 MW. |
| **Caterpillar** | Cat® 3500E-series marine engines can be modified to run on methanol. |
| **China State Shipbuilding Corporation (CSSC) Power Research Institute, Anqing CSSC Diesel Engine, and Hudong Heavy Machinery** | Developed the 6M320DM methanol fuel engine, first ignited on August 28. The engine can be adapted to various ships of up to 20,000 GT. |
| **Hyundai Heavy Industries - Engine & Machinery Division (HHI-EMD)** | 14 methanol dual-fuel, two-stroke engines delivered, and 17 more on order (as of Feb 2022). |
| **MAN Energy Solutions** | ME-LGIM two-stroke dual-fuel methanol engines have accumulated more than 145,000 hours of operation. Four-stroke methanol engines are currently being developed. |
| **mtu Marine solutions (by Rolls-Royce)** | Launching methanol engines based on the mtu Series 4000 from 2026, and fuel cells from 2028. |
| **Nordhavn Power Solutions A/S** | Offers 13 liter/6 cylinder and 16 liter/8 cylinder marine methanol engines, in partnership with ScandiNAOS. |
| **Wärtsilä** | W32 and W46 methanol engines already in the market draws from the experience accumulated since 2015 on the conversion of a Wärtsilä Z40 engine and its operation in the ropax vessel Stena Germanica.<br>Additionally, two-stroke engine retrofits in collaboration with MSC. |
| **WinGD and HSD Engine** | Methanol fueled engines under development in a joint development program. It aims to launch the first engines by 2024. |

In terms of performance, Waterfront Shipping Canada reports having reliably operated dual-fuel methanol two-stroke engines[53] for more than 145,000 hours and has 19 vessels capable of running on the fuel. Test results show methanol offering around 2 percent better specific fuel oil consumption than conventional fuels.[54]

Marinvest Shipping, one of Waterfront Shipping's partners, has been using methanol for five years. Dual-fuel engine reliability is enhanced by having automatic failover between fuel types, which kicks in if a problem with one of the fuels is detected for example if methanol vapors are detected. Dual-fuel engines have more components than single-fuel variants, which can lead to an up to 7 percent increase in maintenance costs.[55]

However, dual-fuel engines are advantageous to shipowners because they give vessels flexibility to switch to lower-priced fuels depending on market conditions. When used on its own, methanol burns cleanly, with much lower $SO_X$ and particulate emissions than conventional oil fuels.[56]

Methanol also has a lower adiabatic flame temperature than conventional fuels such as diesel. This means engine cylinders can operate at lower peak temperatures than with standard fuels, limiting the formation of $NO_X$. This may not be enough to comply with IMO Tier III requirements on $NO_X$ if methanol is used on its own. But when blended with water in a high-pressure injection system, it is possible to meet Tier III standards without the need for selective catalytic reduction (SCR) or exhaust gas recirculation (EGR).

53 MAN Energy Solutions. (2021, July 19). Methanol ExpertTalk Shipowner and Charterer. Retrieved November 19, 2022, from https://www.youtube.com/watch?v=_mCkvOr2dDU&t=109s

54 Buitendijk, M. (2020, March 10). Waterfront Shipping: 'Methanol as a marine fuel works'. Retrieved November 19, 2022, from SWZ Maritime: https://swzmaritime.nl/news/2020/03/10/waterfront-shipping-methanol-as-a-marine-fuel-works/

55 MAN Energy Solutions. (2019, July 29). Methanol ExpertTalk Shipowner. Retrieved November 19, 2022, from https://www.youtube.com/watch?v=Ftxnn-4dqoM&t=367s

56 Methanol needs a small amount of diesel pilot fuel: around 5%.

The water further reduces the heat of combustion, counteracting the $NO_X$ formation that happens at the high temperatures typical of most highly efficient fuel reactions. Adding water to methanol increases fuel consumption overall but only by a small amount—the penalty is unlikely to outweigh the benefit of not having to fit and maintain SCR or EGR equipment.

### Maritime Methanol Fuel Cells

Besides directly fueling two-stroke or four-stroke vessel engines, methanol can be used to drive fuel cells for auxiliary power or propulsion up to megawatt scale.[57]

The benefits of fuel cells over traditional engines are:

- A more compact footprint and multiple configuration options, saving space
- High energy conversion, efficiency, and system power density
- Modular design, allowing for scalability and redundancy
- No moving parts, reducing maintenance
- No $NO_X$, $SO_X$, or PM emissions.

Companies such as Blue World Technologies, e1 Marine, Advent Technologies, and Freudenberg Fuel Cell have developed methanol fuel cells for maritime uses. Fuel cell systems with on-board methanol reformers are now being deployed in pilot projects in the United States, Europe and China.

### Corrosiveness and Choice of Materials

Methanol is corrosive in the presence of aluminum and titanium alloys which are commonly used in fuel systems for natural gas and distillate fuels. To solve this problem, it is possible to apply corrosion-inhibiting additives or coatings, provided they are not likely to be damaged by acidic impurities.

Alternatively, or additionally, non-metallic materials such as nylon, neoprene, or non-butyl rubber can be used in fuel tanks and pipes.[58]

## 3.5. Methanol bunkering

As a liquid fuel at ambient temperature and pressure, methanol bunkering, or refueling, is very similar to MGO or HFO bunkering. The same infrastructure that is used to store and bunker traditional marine fuels can be used for methanol, after minor and inexpensive modifications. There are three main means to bunker methanol: by truck, by barge, and terminal.

There is ample experience in truck to ship methanol bunkering. Since 2015, the ropax ferry Stena Germanica has been bunkering methanol delivered by truck. Other ships that have been bunkered by road include MV Undine, Stena Scanrail, and the Viking Mariella. There is much experience in loading, transporting, and unloading methanol by road transport, and many of the same procedures apply to methanol bunkering.[59]

Barge-to-ship methanol bunkering allows the ship to refuel at port or at sea whilst at anchor. The world's first large-scale barge to ship demonstration was carried out in May 2021, when the methanol

57 Blue World. (n.d.). Market Applications: Maritime. Retrieved November 19, 2022, from Blue World Technologies: https://www.blue.world/markets/maritime/

58 https://safety4sea.com/wp-content/uploads/2021/02/Sustainability-Methanol-as-Marine-Fuel.pdf (Additional information needs to be added to this reference, and this reference needs to be added to the reference list)

59 Fastwater. (2021). Report on methanol supply, bunkering guidelines, and infrastructure. Fastwater. Retrieved November 21, 2022, from https://www.fastwater.eu/images/fastwater/news/FASTWATER_D71.pdf

tanker Takaroa Sun (Waterfront Shipping) was successfully bunkered by the barge MTS Evidence at the port of Rotterdam. This exercise showed that bunkering methanol is feasible and requires similar levels of risk assessment and safety measures as bunkering conventional marine fuels.[60] We have now seen orders for methanol bunker vessels to serve ships at ports in Rotterdam, Norway and Singapore.

Terminal bunkering involves storing methanol at a large tank at port for bunkering ships. This is most suitable for large vessels that operate on a fixed route[61]. One of the instances in which terminal bunkering has been put into practice was when, in October 2022, CSSC Hengyu Energy bunkered three 49,000-ton tankers with 240 tons of methanol from a purpose-built terminal facility.

As more vessel operators transition to methanol as a marine fuel, ports have an opportunity to host methanol production facilities, and methanol storage and bunkering infrastructure. Ports that have signed up to be part of the green corridors of shipping initiative are likely to be among the first to become hubs for renewable methanol production, bunkering and transportation.

A methanol bunkering technical reference document has been prepared by Lloyd's Register in partnership with the Methanol Institute. The International Association of Ports and Harbors is developing methanol bunker checklists, and methanol bunker guidelines are being developed by the two largest ports, Port of Rotterdam and Port of Singapore

## 3.6. Safety

### Fire Hazards and Prevention

Another important factor is that methanol has a low flashpoint (12 °C). This means that 12 °C is the lowest temperature at which vapors emanate from methanol in sufficient quantities to form an ignitable vapor-air mixture. Additionally, methanol's flammable range in dry air is between 6 percent and 36.5 percent and can create an explosive or flammable environment. Methanol burns at a relatively low temperature and its flame is almost invisible to the eye during daytime[62]. Finally, the molecular weight of methanol (32 grams per mole) is slightly higher than that of air (28 grams per mole), as a result methanol vapor tends to accumulate close to the ground. Methanol does not dissipate in enclosed unventilated areas.

These characteristics call for specific safety measures that prevent methanol vapors from forming and the installation of appropriate ventilation, leak detection, heat detection and fire extinguishing equipment.

### Toxicity

Humans metabolize methanol into formic acid, making it toxic if ingested, absorbed through the skin, or inhaled in high concentrations.

Exposure to methanol can cause blindness, kidney failure and, if the dose is high enough or the exposure prolonged, death. Ingesting 10 milliliters of pure methanol can cause critical damage to the optic nerve and the median lethal dose, when ingested, is approximately 100 milliliters.

Methanol poisoning can be counteracted with an antidote such as fomepizole or ethanol. Hemodialysis or hemodiafiltration may be indicated to remove methanol and its toxic by-products from the blood.

60 The Maritime Executive. (2021, May 12). World's First Barge Bunkering with Methanol Demonstrates Potential. Retrieved November 21, 2022, from The Maritime Executive: https://maritime-executive.com/article/world-s-first-barge-bunkering-with-methanol-demonstrates-potential

61 Offshore Energy (2022). Methanol Bunkering Trifecta for CSSC, retrieved on May 14, 2023 from https://www.offshore-energy.biz/methanol-bunkering-trifecta-for-cssc/

62 ABS. (2021). Methanol as a Marine Fuel: Sustainability Whitepaper. ABS. Retrieved November 19, 2022, from https://safety4sea.com/wp-content/uploads/2021/02/Sustainability-Methanol-as-Marine-Fuel.pdf

Bunkering and on-board fuel supply and combustion systems are designed so that crew members do not come into direct contact with methanol. Nevertheless, crews must be adequately trained in handling methanol and knowing how to safely deal with a methanol leak or spill. The IMO's Code of Safety for Ships using Gases or other Low flashpoint Fuels (IGF Code), adopted in November 2020 following six years of review, provides guidelines and mandatory criteria to minimize risks for crew members aboard methanol-fueled ships.

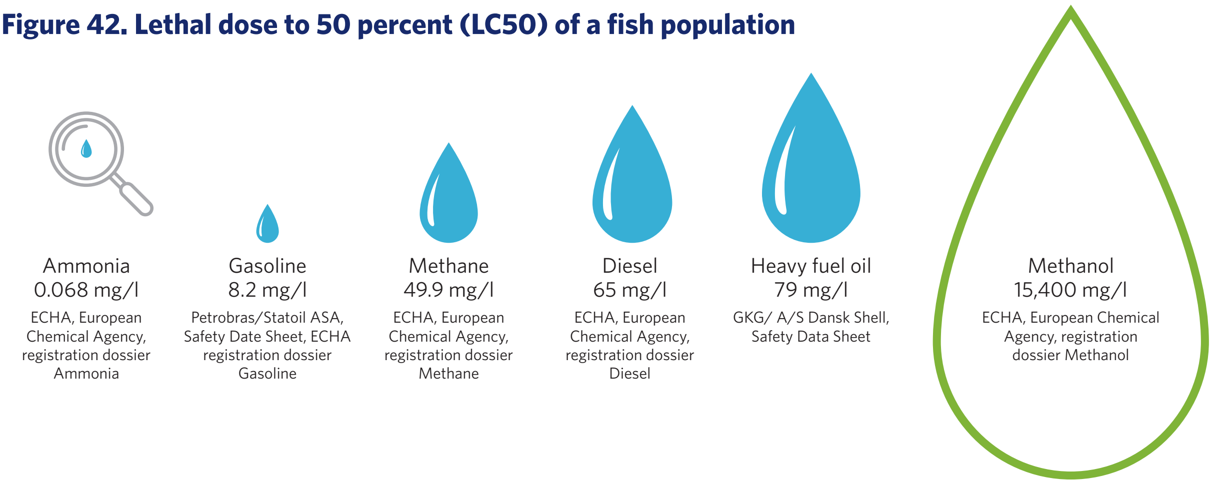
### Environmental: Effects of a Methanol Spill

Methanol is relatively benign from an environmental pollution perspective compared to other fuels because it is fully miscible in water and biodegradable. As a result, a methanol spill would likely have only limited impacts on marine life unless delivered in very high concentrations.

The fact that methanol is fully miscible in water means that it would easily dilute to low concentrations in case of a spill at sea. Additionally, microbes readily breakdown methanol into $CO_2$ and water at concentrations of less than 3000 mg/l. Methanol would last between one and seven days in surface water before dissolving completely.

Methanol is, however, toxic to aquatic organisms at concentrations above 1000 mg/l and especially 10,000 mg/l and above. It is useful, however, to put these figures into context by comparing methanol to other marine fuels. The toxicity of a chemical is often presented as Lethal Concentration 50 (LC50), which is the dose that is lethal to 50 percent of organisms in a given population. In a body of water, the LC50 of fish for methanol is 15,400 mg/l, compared to just 79 mg/l for HFO. In other words, other things being equal, you would need to spill 200 times more methanol than HFO to kill the same number of fish. By this measure of toxicity, other fuels are even more lethal to fish than HFO and all fuels are more toxic than methanol. Further, the LC 50 for ammonia is just 0.068 mg/l, which makes ammonia highly toxic to marine environments.

**Figure 42. Lethal dose to 50 percent (LC50) of a fish population**




Additionally, the effects of short-term methanol exposure on marine life are temporary and reversible.

The relatively low risk of environmental damage from methanol spills compared to other fuels means it is possible to carry out methanol bunkering at sea. Further, methanol's lower environmental risk from spills coupled with the fact that methanol combustion reduces emissions of particulate matter or black carbon by 95 percent means that methanol is ideally suited to sailing in sensitive environments such as the Arctic.

## 3.7. Costs

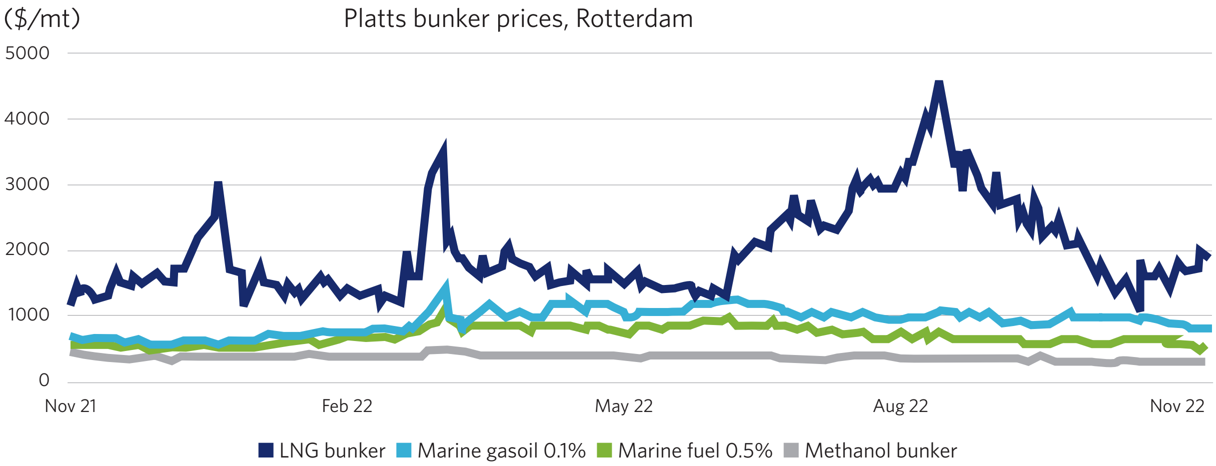
### Current Fuel Costs

According to S&P Global Commodity Insights figures, methanol traded at lower prices, on a dollar per ton basis, than MGO, HFO and LNG at the Rotterdam bunkering hub from November 2021 to November 2022 (See Figure 43).

Natural gas prices spiked towards the end of 2021, amid supply tightness ahead of winter, and more spikes emerged after the Russian invasion of Ukraine in February 2022. The surging natural gas price impacted the LNG price, but also had a placed upward pressure on methanol prices, as most methanol is made from natural gas.

Methanol appears very attractively priced, especially under the high energy price environment seen since the second half of 2021.

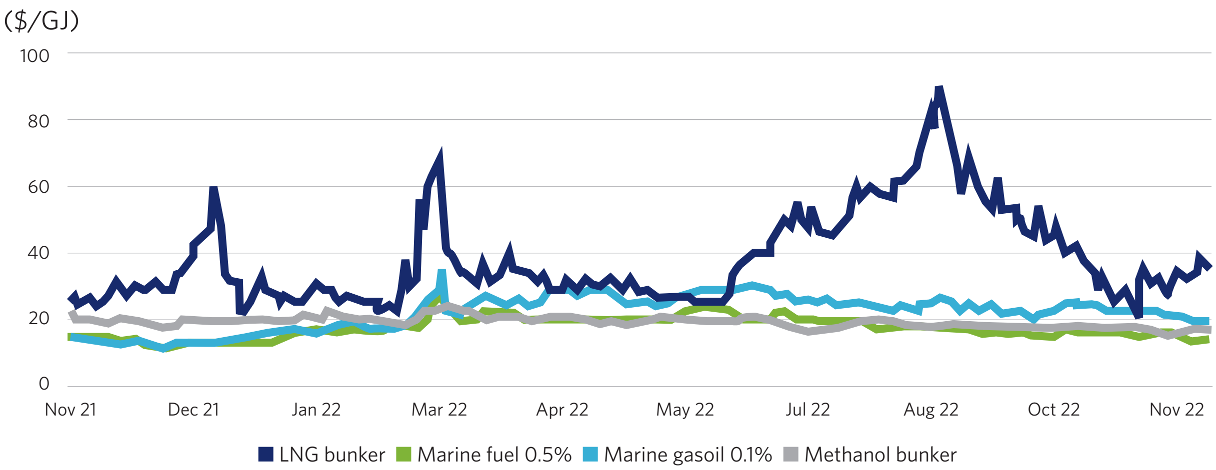
**Figure 43. Bunker Prices of Methanol, HFO, LNG, and MGO at the Rotterdam Hub ($/ton)**




Source: S&P Global Commodity Insights

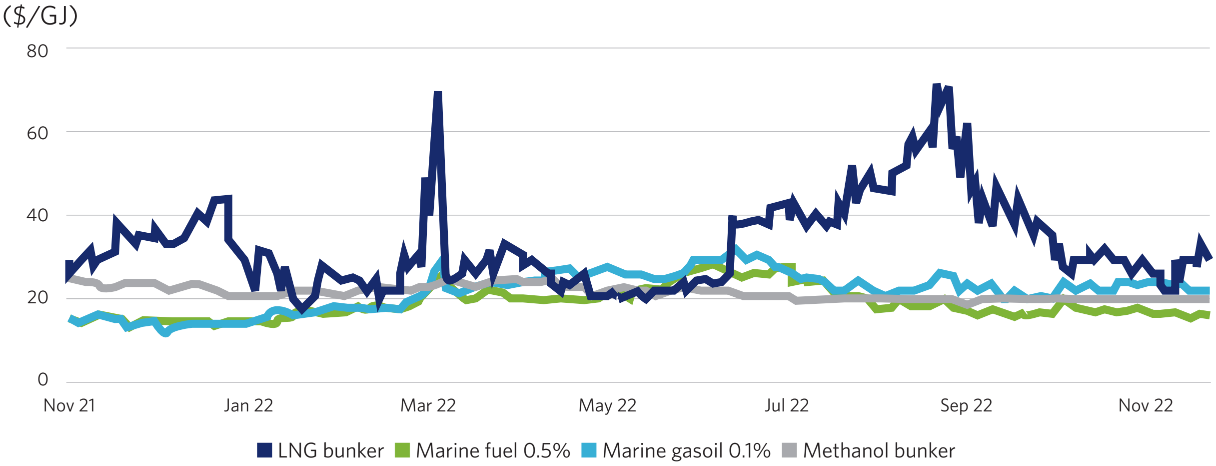
However, when incorporating the relevant energy density factor to compare the different fuels on a like-for-like basis, HSFO typically becomes the cheapest, although methanol often traded at lower prices than LNG and MGO in the Rotterdam bunkering hub (Figure 44) as well as in Singapore (Figure 45).

**Figure 44. Fuel Prices Considering Calorific Value – Rotterdam Bunker Fuel Prices ($/GJ)**




Source: S&P Global Commodity Insights

**Figure 45. Fuel Prices Considering Calorific Value – Singapore Bunker Fuel Prices ($/GJ)**



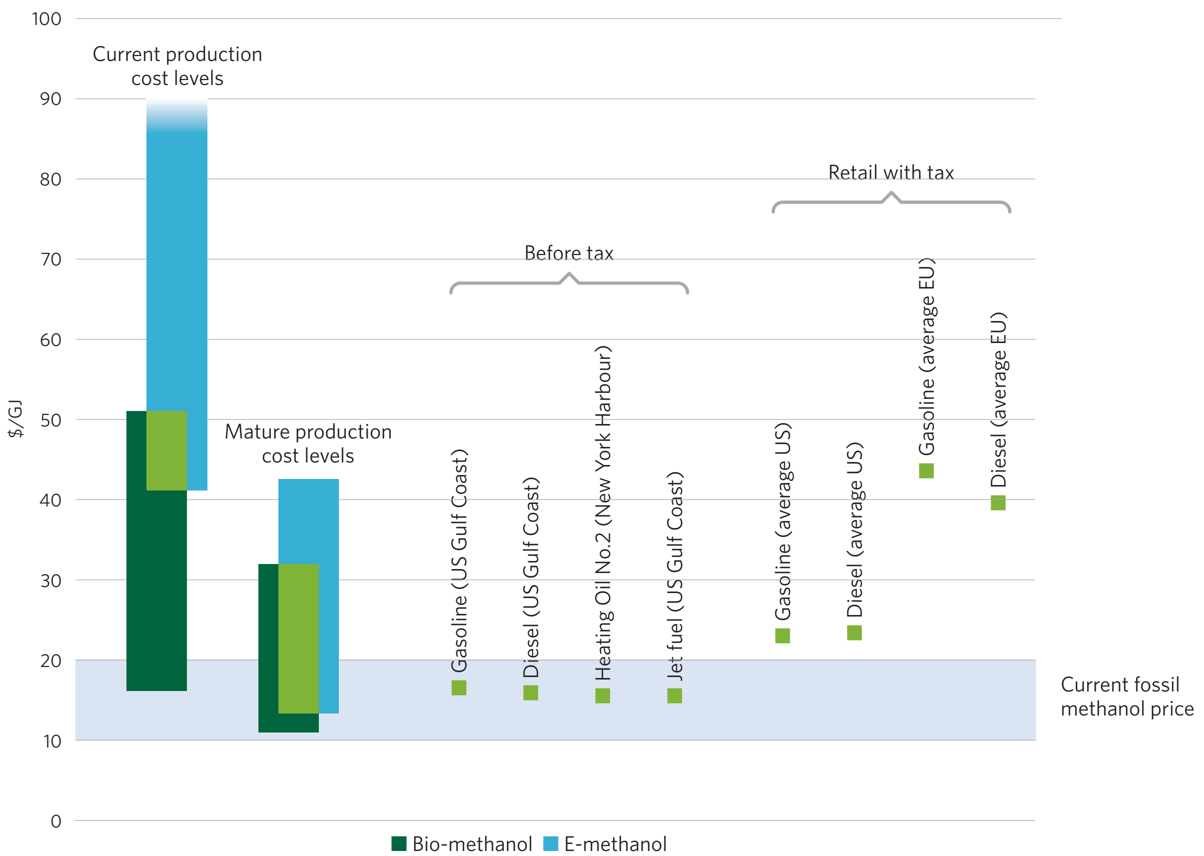

Source: S&P Global Commodity Insights

## Fuel Cost Projections

According to the Methanol Institute, conventional methanol is available at more than 120 ports across the globe, while worldwide production capacity in 2020 was more than 131 million tons, according to data from S&P Global.

There has also been a surge in orders of methanol dual-fuel vessels. According to Platts Analytics, at least 23 such vessels were in order books as of H1 2022 for delivery by 2025, added to the 16 already

**Figure 46. Comparison of Renewable Methanol with Other Fuels on a Price per Unit of Energy Basis ($/GJ)**




Source: IRENA (2021)

on the water. The database DNV Alternative Fuels Insight puts the total number of methanol vessels at 103, including ships in operation and on order.[63]

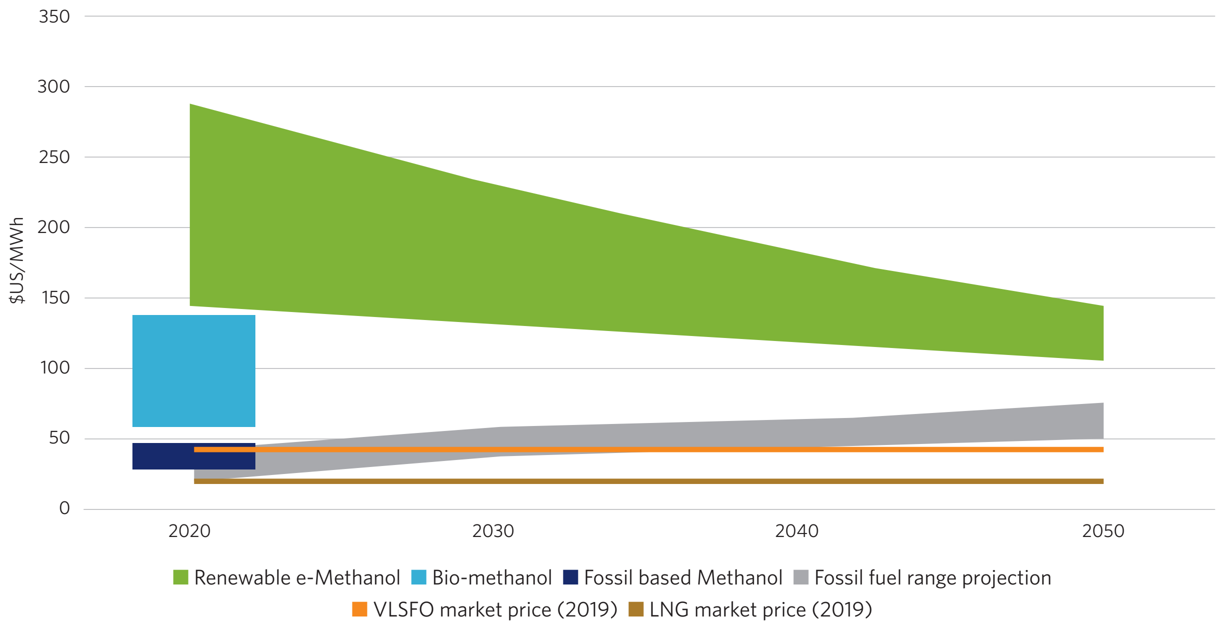
However, many of these operators have made a commitment to run their vessels on green or carbon neutral methanol, a fuel that currently doubles conventional methanol on price and is far less available than the fossil chemical. Renewable methanol production costs are dependent on the raw material and production process.

Costs of bio-methanol and e-methanol are expected to decrease as production capacity increases. By 2050, production costs of both types of renewable methanol are expected to be comparable to current costs of certain fossil fuels, at 12 to 43 $/GJ for e-methanol and 11 to 32 $/GJ for bio-methanol (See Figure 46).[64]

Figure 47 shows the expected evolution of renewable e-methanol and bio-methanol production costs, according to IRENA (2021). Lowering renewable e-methanol production costs depends heavily on the development of cheaper carbon capture and utilization technologies.[65]

According to Platts Analytics' reference case for July, alternative fuels will account for 2 percent of global bunker fuel demand of 328 million tons per year in 2030, compared with almost zero in 2022. Methanol is expected to make up 34.3 percent of the alternative fuels demand, hydrogen 18.6 percent and ammonia 14.7 percent.

**Figure 47. E-methanol and biomethanol production cost projections**



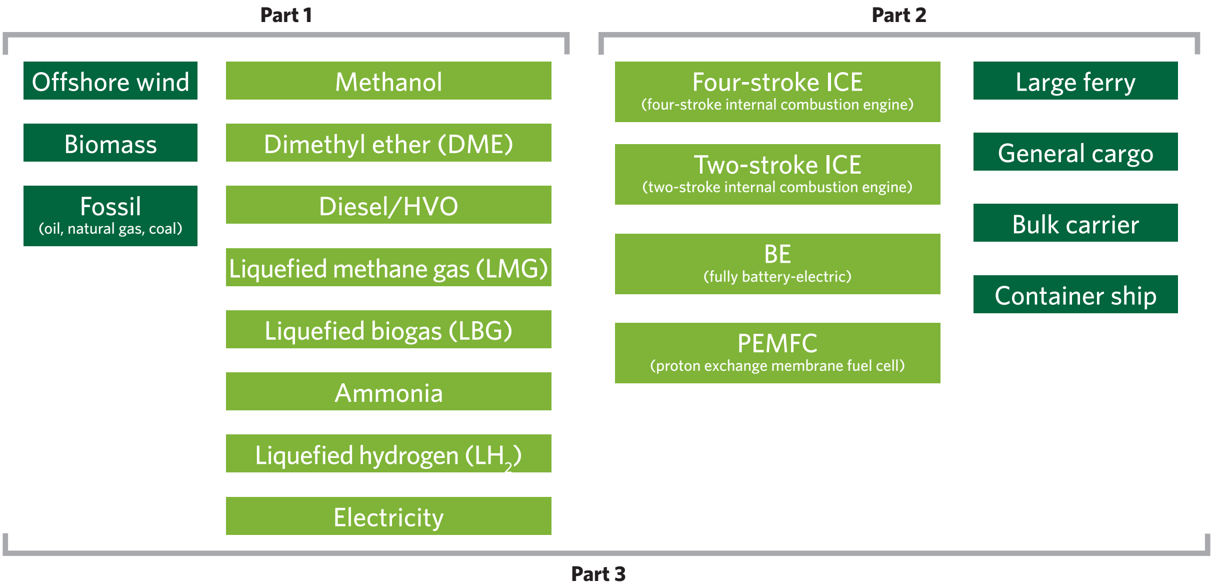

Note: Figure refers to the cost of fuel production. The total cost of ownership (e.g., machinery, storage and other) is not captured.
Source: Methanol costs: IRENA (2021); fossil fuel cost projections: Lloyd's Register (2019)

63 DNV Alternative Fuels Insight, retrieved April 7, 2023 from https://afi.dnv.com/statistics/16486173-4f14-4cc5-b9f6-f2f4b4c47a15 (This reference needs to be completed and added to the reference list).

64 IRENA and Methanol Institute. (2021). Innovation Outlook: Renewable Methanol, Abu Dhabi: International Renewable Energy Agency. Retrieved November 19, 2022, from https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol

65 IRENA. (2021). A pathway to decarbonise the shipping sector by 2050. Abu Dhabi: International Renewable Energy Agency. Retrieved November 19, 2022, from https://irena.org/publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050

**Figure 48. Marine Fuels, Propulsion Technologies, and Ship Types and Usage Considered in the Aalborg and Chalmers University Study (2021)**




Note: Fossil fuels are not assessed but included as a comparison
Source: Brynolf, S., Grahn, R., Korberg, A., & Skov, I. (2021, May).

## Total Cost of Ownership

Fuel costs are one of the key indicators for shipping companies seeking alternative fuels. However, to have a full understanding of how much it costs to run a ship on a certain type of fuel, it is crucial to also consider other factors such as: type of ship and usage, propulsion technology, onboard fuel storage costs, and the cost of lost cargo space.

A 2021 study by Aalborg University and Chalmers University considered multiple factors to arrive at the total cost of ownership for several types of ship, propulsion technologies and fuel types (summarized in Figure 48) and found that methanol is the lowest cost fuel for almost all fuel-propulsion combinations (Figure 49).

This analysis highlights that ICE are likely to continue being the most cost-effective technology. When fuel costs are higher, the cost effectiveness of fuel cells improves thanks to their higher efficiency. Similarly, longer journeys at sea favor the economics of fuel cells. However, the efficiency of fuel cell systems would need to be 15 to 20 percent higher than ICE's to replace four-stroke engines. Replacing the more efficient two-stroke engines would require even higher fuel efficiency and lower capital costs.

Bio-methanol achieved the lowest TCO across four ship types and all utilization rates, although costs were significantly higher than those of MGO, which was used as a benchmark. The study concludes that regardless of which fuels prevail, "the shipping sector must be ready to pay a significantly higher price for a renewable fuel on a fuel market with generally higher prices than today".[66]

66 Brynolf, S., Grahn, R., Korberg, A., & Skov, I. (2021, May). Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. Renewable and Sustainable Energy Reviews, 142. https://doi.org/10.1016/j.rser.2021.110861

## Figure 49. Total Cost of Ownership by Type of Ship (Millions of euros per year, base case)

| | | Large Ferries | | | | | | | | | General Cargo Ships | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Utilization/trip** | | Short | | | Medium | | | Long | | | Short | | Medium | | Long | |
| **Propulsion** | | ICE | FC | BE | ICE | FC | BE | ICE | FC | BE | ICE | FC | ICE | FC | ICE | FC |
| **MGO** | | 0.9 | | | 1.7 | | | 2.4 | | | 1.3 | | 1.5 | | 1.8 | |
| **Biofuels** | Biomethanol | 2.0 | 4.2 | | 3.9 | 5.7 | | 5.7 | 7.2 | | 3.0 | 3.8 | 3.7 | 4.4 | 4.6 | 5.1 |
| | BioDME | 2.3 | | | 4.2 | | | 6.2 | | | 3.3 | | 4.0 | | 4.9 | |
| | Biodiesel | 2.7 | | | 5.2 | | | 7.6 | | | 4.0 | | 4.8 | | 5.8 | |
| | BioLMG | 3.0 | 4.9 | | 5.4 | 6.8 | | 7.8 | 8.7 | | 4.2 | 4.8 | 5.1 | 5.6 | 6.2 | 6.6 |
| | BioLBG | 2.8 | 4.8 | | 5.1 | 6.6 | | 7.4 | 8.4 | | 4.0 | 4.6 | 4.8 | 5.4 | 5.9 | 6.4 |
| | HVO | 2.4 | | | 4.6 | | | 6.8 | | | 3.6 | | 4.3 | | 5.2 | |
| **Bio-electrofuels** | E-Biomethanol | 2.6 | 4.7 | | 4.9 | 6.6 | | 7.3 | 8.5 | | 3.8 | 4.5 | 4.7 | 5.2 | 5.8 | 6.1 |
| | E-BioDME | 2.9 | | | 5.4 | | | 7.9 | | | 4.1 | | 5.0 | | 6.2 | |
| | E-Biodiesel | 3.2 | | | 6.2 | | | 9.2 | | | 4.8 | | 5.8 | | 7.0 | |
| | E-BioLMG | 3.6 | 5.4 | | 6.6 | 7.8 | | 9.6 | 10.2 | | 5.1 | 5.6 | 6.2 | 6.5 | 7.7 | 7.7 |
| | E-BioLBG | 3.6 | 5.3 | | 6.5 | 7.7 | | 9.5 | 10.1 | | 5.1 | 5.5 | 6.1 | 6.5 | 7.5 | 7.7 |
| **Electrofuels** | E-methanol | 3.3 | 5.3 | | 6.5 | 7.8 | | 9.7 | 10.3 | | 5.0 | 5.5 | 6.1 | 6.3 | 7.6 | 7.5 |
| | E-DME | 3.7 | | | 7.0 | | | 10.3 | | | 5.4 | | 6.5 | | 8.0 | |
| | E-diesel | 4.3 | | | 8.4 | | | 12.5 | | | 6.5 | | 7.8 | | 9.5 | |
| | E-LMG | 4.3 | 5.9 | | 8.0 | 8.9 | | 11.8 | 11.9 | | 6.2 | 6.4 | 7.6 | 7.6 | 9.3 | 9.0 |
| | Ammonia | 3.7 | 5.5 | | 6.9 | 8.0 | | 10.2 | 10.6 | | 5.3 | 5.6 | 6.4 | 6.5 | 8.0 | 7.8 |
| **$LH_2$** | | 4.7 | 5.3 | | 8.8 | 8.6 | | 13.0 | 11.9 | | 7.0 | 6.5 | 8.7 | 8.0 | 11.0 | 9.9 |
| **Electricity** | | | | 2.8 | | | 5.5 | | | 8.3 | | | | | | |

Low TCO M€/year

High TCO M€/year

| | | Bulk Carrier Ships | | | | | | Container Ships | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Utilization/trip** | | Short | | Medium | | Long | | Short | | Medium | | Long | |
| **Propulsion** | | ICE | FC | ICE | FC | ICE | FC | ICE | FC | ICE | FC | ICE | FC |
| **MGO** | | 3.2 | | 3.7 | | 4.4 | | 13.5 | | 16.1 | | 17.5 | |
| **Biofuels** | Biomethanol | 7.2 | 9.7 | 8.9 | 11.3 | 11.3 | 13.3 | 30.9 | 39.7 | 38.4 | 46.3 | 42.4 | 49.9 |
| | BioDME | 7.7 | | 9.5 | | 11.8 | | 33.2 | | 40.9 | | 45.1 | |
| | Biodiesel | 9.1 | | 10.9 | | 13.2 | | 39.8 | | 48.3 | | 52.6 | |
| | BioLMG | 9.9 | 11.9 | 12.2 | 13.8 | 15.0 | 16.3 | 42.4 | 48.9 | 52.5 | 57.9 | 58.5 | 63.2 |
| | BioLBG | 9.4 | 11.4 | 11.6 | 13.3 | 14.3 | 15.7 | 40.3 | 47.0 | 49.9 | 55.6 | 55.6 | 60.7 |
| | HVO | 8.2 | | 9.8 | | 11.9 | | 35.8 | | 43.4 | | 47.3 | |
| **Bio-electrofuels** | E-Biomethanol | 9.0 | 11.4 | 11.1 | 13.2 | 14.0 | 15.7 | 39.0 | 46.9 | 48.2 | 55.1 | 53.1 | 59.5 |
| | E-BioDME | 9.6 | | 11.8 | | 14.6 | | 41.7 | | 51.2 | | 56.4 | |
| | E-Biodiesel | 11.0 | | 13.1 | | 15.9 | | 48.0 | | 58.3 | | 63.5 | |
| | E-BioLMG | 12.1 | 13.8 | 14.7 | 16.1 | 18.2 | 19.2 | 51.8 | 57.4 | 64.0 | 68.3 | 71.0 | 74.5 |
| | E-BioLBG | 11.9 | 13.6 | 14.5 | 16.0 | 17.9 | 18.9 | 51.1 | 56.7 | 63.1 | 67.5 | 70.0 | 73.7 |
| **Electrofuels** | E-methanol | 11.7 | 13.8 | 14.3 | 16.1 | 17.9 | 19.3 | 50.8 | 57.6 | 62.7 | 68.1 | 68.9 | 73.7 |
| | E-DME | 12.4 | | 15.1 | | 18.7 | | 54.0 | | 66.3 | | 72.9 | |
| | E-diesel | 14.8 | | 17.7 | | 21.5 | | 64.7 | | 78.7 | | 85.8 | |
| | E-LMG | 14.5 | 16.0 | 17.7 | 18.8 | 21.8 | 22.4 | 62.6 | 67.1 | 77.2 | 80.1 | 85.4 | 87.4 |
| | Ammonia | 12.5 | 14.2 | 15.4 | 16.8 | 19.3 | 20.2 | 53.9 | 59.3 | 66.3 | 70.4 | 73.1 | 76.4 |
| **$LH_2$** | | 16.6 | 16.5 | 21.4 | 20.7 | 27.5 | 26.2 | 71.4 | 70.2 | 90.8 | 87.6 | 102.6 | 98.2 |

Low TCO M€/year — High TCO M€/year

Source: Brynolf, S., Grahn, R., Korberg, A., & Skov, I. (2021, May).

Notes: Batteries were only considered in the large ferries case, given that their lower energy density makes them unsuitable for deep sea shipping. Methanol costs: e-methanol €119 per MWh, e-biomethanol €91 per MWh, biomethanol €69 per MWh, electricity €33 per MWh. Nominal propulsion capacity: Large ferries (11 MW), General Cargo (6 MW), Bulk Carrier (15 MW), Container ship (55 MW). Full set of assumptions available at the source.

## 3.8. The Competitive Advantages of Marine Methanol

As seen throughout this report, employing methanol as a marine fuel offers significant advantages to ship operators:

- **Availability:** Methanol is already widely available and easy to source. Methanol production capacity is expected to expand fivefold by 2050, reaching 500 million tons, 80 percent of which will be carbon neutral e-methanol and bio-methanol.
- **Emissions:** Ship operators who still rely on traditional shipping fuels, such as HFO and MGO, can dramatically lower pollutant emissions by switching to methanol. Marine methanol produces 99 percent less $SO_X$, 95 percent less PM, and up to 80 percent less $NO_X$ than MGO.

  $CO_2$, emissions from methanol vary depending on the source. At one end the spectrum, methanol produced from natural gas has higher average carbon emissions than HFO and MGO on a well-to-wake basis. At the other end of the spectrum, e-methanol and bio-methanol produce only a fraction of the emissions of dominant shipping fuels. Additionally, unlike other fuels, there are no methane slip concerns with marine e-methanol and bio-methanol.

- **Ease of handling:** Unlike fuels that require cryogenic equipment, methanol remains liquid at ambient temperature and pressure. Thanks to this, it can be transported, stored and bunkered with existing infrastructure after relatively simple modifications. This translates into significantly lower infrastructure costs. Methanol is routinely shipped all over the world, and safety guidelines are well developed, understood and codified in regulations.
- **Toxicity:** Methanol is fully miscible in water and biodegradable. Thanks to this, a methanol spill at sea would have minimal and temporary effects on marine life. This stands in contrast to all other fuels, which are highly toxic to marine life.
- **Cost effectiveness:** Low and carbon neutral methanol is consistently regarded as the most cost-effective marine fuel on a total cost of ownership basis. However, low carbon fuels are likely to remain more expensive than fossil fuels, this suggests that the widespread adoption of low-carbon marine fuels requires policy interventions such as a price on carbon.

# 4. Case Studies: Marine Methanol in Shipping

An increasing number of leading vessel operators are choosing methanol as a marine fuel. This section delves into the experiences of four such operators:

- AP Moller-Maersk
- Methanex Waterfront Shipping
- Proman Stena Bulk
- Stena Germanica

## 4.1 A.P. Moller – Maersk Bets on Green Methanol

A.P. Moller-Maersk is an integrated container logistics company working to connect and simplify its customers' supply chains. The second-largest shipping company in the world, Maersk operates in more than 130 countries and employs around 100,000 people. In August 2021, the company announced it would be accelerating its fleet decarbonization plans with the delivery of eight large ocean-going vessels operating on carbon-neutral methanol.

The number of dual-fuel engines on order has now gone up to 19, with feeder vessels arriving in 2023 and the first large ocean-going vessel due to enter into operation in the first quarter of 2024. Maersk is spending $7 billion on the fleet upgrade. The vessels are being built by Hyundai Heavy Industries and have a nominal capacity of about 16,000 twenty-foot equivalent unit (TEU) containers.

They will feature a methanol propulsion configuration developed in collaboration with makers including MAN Energy Solutions, Hyundai and Alfa Laval. Maersk says the propulsion units represent a significant scale up of the technology, from a previous size limit of around 2,000 TEU. The vessels will be classed by the American Bureau of Shipping and sail under Danish flags.

The series will replace older vessels, with the first eight ships generating annual $CO_2$ emissions savings of around 1 million tons. In its 2021 announcement, Maersk said additional capital expenditure for the dual-fuel vessels would be up to 15 percent of the total price. In October 2022, Maersk announced the order of an additional six vessels with incremental pricing per vessel reduced to 8-12 percent compared with standard diesel-fueled vessels. The move to methanol fuel follows more than half of Maersk's 200 largest customers, including Amazon, Disney, H&M Group, HP, Levi Strauss & Co, Microsoft and Novo Nordisk, setting or planning science-based carbon reduction or zero-carbon targets for their supply chains.

"We are investing in methanol as one of several promising technologies of the future," says Berit Hinnemann, interim head of green fuels sourcing at Maersk. "The reasons for our belief in green methanol are three-fold: speed, optionality and cost. Green methanol allows us to make an impact on greenhouse gas reduction this decade, and green methanol is feasible to scale up from a cost perspective.

"We also work on other promising future technologies such as green ammonia but find that ammonia as a shipping fuel is not ready to be implemented yet and needs further technical and safety work."

Despite this, Hinnemann says getting hold of green methanol is not easy at present, since green methanol is only produced in small amounts today and production needs to be scaled up. The company has signed seven green methanol partnerships around the world, with the most recent, with Chinese bioenergy enterprise Debo, being inked in August 2022. The agreement with Debo will see the provider developing a Chinese bio-methanol project for Maersk with capacity of 200,000 tons per year to start commercial operation by fall 2024.

In March 2022, Maersk announced partnerships with CIMC ENRIC, European Energy, Green Technology Bank, Ørsted, Proman and WasteFuel, with the intent of sourcing at least 730,000 tons of green methanol per year by end of 2025. "The most important challenge is the availability of green methanol at scale, and here partnerships across the value chain are key to accelerate the development and scale-up," Hinnemann says.

**Figure 50. Strategic Partnerships Signed by AP Moller-Maersk to Source Renewable Methanol**

| Strategic Partners | Type of fuel | Production Capacity in 2024 (end of year) tons/year | Production capacity added after 2015 tons/year | Production capacity added after 2025 tons/year | Geography |
|---|---|---|---|---|---|
| **CIMC ENRIC** | Bio-methanol | 50,000 | | 200,000 | China |
| **Debo** | Bio-methanol | 200,000 | | | |
| **European Energy** | E-methanol | | 2-300,000 | | North & South America |
| **GTB** | Bio-methanol | 50,000 | | 300,000 | China |
| **Orsted** | E-methanol | | 300,000 | | North America |
| **Proman** | Bio and e-methanol | | 100,000 | | North America |
| **WateFuel** | Bio-methanol | 30,000 | | | South America |
| **Total** | | 330,000 | 6-700,000 | 500,000 | |

Source: Green Maritime Methanol, 2021

"We also need infrastructure at port for storage and bunkering, and here green corridors and other initiatives may play a key role", says Berit Hinnemann.

## 4.2 Waterfront Shipping Pioneers Methanol Use

Vancouver, Canada-based Waterfront Shipping is a maritime transport subsidiary of Methanex Corporation, the world's largest producer and supplier of methanol. Both companies have been pioneers in promoting methanol in shipping, and Waterfront Shipping, a global marine transportation firm specializing in bulk chemicals and clean petroleum products—along with MAN and its partners—have been at the forefront of efforts to develop a fleet based on the fuel that is being widely adopted by others today.

The company has been operating methanol-fueled vessels since 2016, and currently has 19 dual-fuel ships in its 30-strong fleet of deep-sea tankers, which are a decade old on average and range in size from 3,000 to 49,999 deadweight tons (dwt).

The company reports the shift to methanol fuel has been safe and straightforward, with hundreds of hours of bunkering taking place during cargo loading. Since 2016, the company has been bunkering at ports where it doesn't produce methanol including Ulsan and Onsan, South Korea; Houston, USA; Rotterdam, Netherlands; and Taicang, China. In May 2021, the company also carried out the world's first barge-to-ship bunkering exercise, at the Port of Rotterdam, using a conventional barge with minor modifications and a minimal incremental cost.

The move saw a commercial bunker barge refueling Waterfront Shipping's Takaroa Sun, a long-term chartered vessel with a two-stroke, dual-fuel engine owned by Nippon Yusen Kaisha and accorded special mention in the Green Ship of the Year awards. The nominal cost to equip Waterfront Shipping's vessels with methanol dual-fuel engines and associated fuel delivery systems has been relatively minor compared to the cost to equip ships with the ability to run on other alternative or novel fuel types, such as LNG, ammonia or hydrogen.

**Figure 51. Barge-to-Ship Methanol Bunkering at the Port of Rotterdam**

Like diesel, methanol is a liquid at ambient temperature and pressure, so the main changes required are a new fuel delivery system and minor modifications to the ships' infrastructure, such as adding storage space, cofferdams and installing double-walled piping. Diesel engines can be adapted with a manufacturer kit that adds an extra methanol fuel system and includes adjustments to the valves and the injector. Similarly, methanol requires relatively few bunkering adaptations and can largely rely on the infrastructure used for diesel.

Waterfront Shipping says methanol is cost-competitive on an energy-equivalent basis with low-sulfur fuels such as MGO, while offering slightly higher fuel efficiency than conventional options. The company is now adopting dual-fuel vessels that use water-blending technology to reduce $NO_x$ emissions to within Tier III levels, which avoids the need for investment in SCR systems.

In July 2021, Mitsui OSK Lines, which has a fleet of around 800 vessels, took an equity position in Waterfront Shipping as part of a strategic partnership with Methanex Corporation. "Methanol has emerged as a leading alternative fuel in the transition to a low carbon future and with the use of renewable methanol, as we are able to produce at our Geismar facility, would deliver on the IMO's 2050 carbon goals," says Paul Hexter, President, Waterfront Shipping.

In early 2023, Waterfront Shipping in partnership with Mitsui OSK Lines (MOL), completed the first-ever net zero voyage fuelled by bio-methanol, demonstrating that the pathway to net-zero emissions and the decarbonization of the shipping industry is possible today with methanol as a marine fuel. The voyage was demonstrated with The Cajun Sun, (operated by WFS and chartered from MOL) between Geismar and Antwerp, Belgium. By blending ISCC-certified bio-methanol that has negative carbon intensity with natural gas-based methanol, net-zero greenhouse gas emissions on a lifecycle basis were achieved for the 18-day trans-Atlantic voyage.

**Figure 52. Waterfront Shipping's Mari Innovator**

Note: The Mari Innovator the first third generation dual-fuel methanol vessel in Waterfront Shipping's Fleet.

"Methanol is already a large global commodity chemical and fuel and hence we would expect the supply side to grow to match new demand. This would be like how the industry responded to the growth of methanol to olefin use over the past decade."

**First ports to bunker methanol**

The following is a list of ports where Methanex/Waterfront Shipping was the first to load and/or demonstrate methanol bunkering as a marine fuel (locations where Methanex does not have methanol production are in red):

- Ulsan, South Korea (Hyundai HMD Shipyard; since 2016)
- New Plymouth, New Zealand (since June 2016)
- Geismar, USA (since August 2016)
- Trinidad (since April 2017)
- Punta Arenas, Chile (since February 2019)
- Houston, USA (since June 2020)
- Rotterdam, Netherlands (inaugural global bunkering demonstration, May 2021)
- Onsan, South Korea (May 2022)
- Taicang, China (August 2022)

## 4.3 Proman Stena Bulk: Methanol-Fueled Chemical Tankers

Proman Stena Bulk Limited is a joint venture formed in 2019 between Proman, a Swiss-headquartered integrated energy company and leading global methanol producer, and Stena Bulk, one of the world's leading tanker shipping companies. In August 2022, the joint venture announced that its two operational methanol-fueled tankers, the Stena Pro Patria and Stena Pro Marine, were among the first vessels to bunker methanol in Ulsan, South Korea.

Proman Stena Bulk chose methanol because it is immediately available as a fuel, available at more than 120 key bunkering ports, and relies on proven engine and bunker infrastructure technologies. Plus, it is easy and safe to handle. "Most importantly, methanol can enable both immediate and long-term $CO_2$ and GHG emissions reductions," says Anita Gajadhar, Managing Director Marketing, Logistics and Shipping at Proman.

"It futureproofs assets and sets the industry up for a proven low-carbon pathway, as we stage towards lower-carbon and renewable methanol in the coming years."

**Figure 53. Stena Pro Patria**


Note: Stena Pro Patria is the first of three 49,900 dwt methanol dual-fuel MR tankers by Proman Stena Bulk.

Both Proman and Stena Bulk have extensive experience working with and around methanol and the experience of running two vessels on the fuel has been positive so far, Gajadhar reports. "Methanol is easy to handle, and we have been able to build rigorous safety procedures for crews," she comments.

"From an emissions perspective, we are already seeing the virtual elimination of $SO_X$ and particulate matter from the two tankers that are currently operational, and a significant reduction in $NO_X$. While the vessels are still very new, we would also expect a much cleaner engine room in the longer term as a result of methanol's clean-burning qualities."

Proman Stena Bulk estimates methanol-fueled vessels to be up to 10 percent more capital intensive when compared to a conventional vessel, but this cost is seen as marginal compared to the upfront cost of ships equipped to use other future fuels, such as LNG. Wider infrastructure costs are minimal, the company reports, particularly given methanol's availability at key bunkering ports and its potential to use existing infrastructure.

Nevertheless, Proman Stena Bulk is working with ports and global bunker providers to support the development of wider methanol bunkering infrastructure and guidelines. These efforts are already bearing fruit, with the joint venture completing methanol ship-to-ship methanol bunkering in Rotterdam in August 2022 with minimal additional costs and preparation.

The first few months of methanol experience have seen operational expenditure increasing by about 3 percent compared to conventional vessels. However, most of these costs were for crew IGF Code training or initial increased maintenance requirements, so there is "every indication" that operational costs will reduce over time, the company says.

"We believe that more focus should be placed on the pathway that methanol enables," says Gajadhar. "There is no reason not to make the switch today: immediate and significant emissions reductions are achievable now, and owners and operators are then set up for increasing blends of low-carbon and renewable methanol to meet incoming regulatory targets and environmental ambitions."

Methanol's flexibility and proven low-carbon pathway means that a methanol vessel built today can meet every mooted emissions reduction target between now and 2050, she adds.

"It's clear that the marine fuel mix will become more fragmented and diverse," Erik Hånell, President and CEO, Stena Bulk, adds. "Indeed, we need many solutions – fuels and technologies – to achieve a truly decarbonized sector. Methanol is one option amongst many, but faced with the requirement to act now, ship owners will see the fuel as a key solution in the near term."

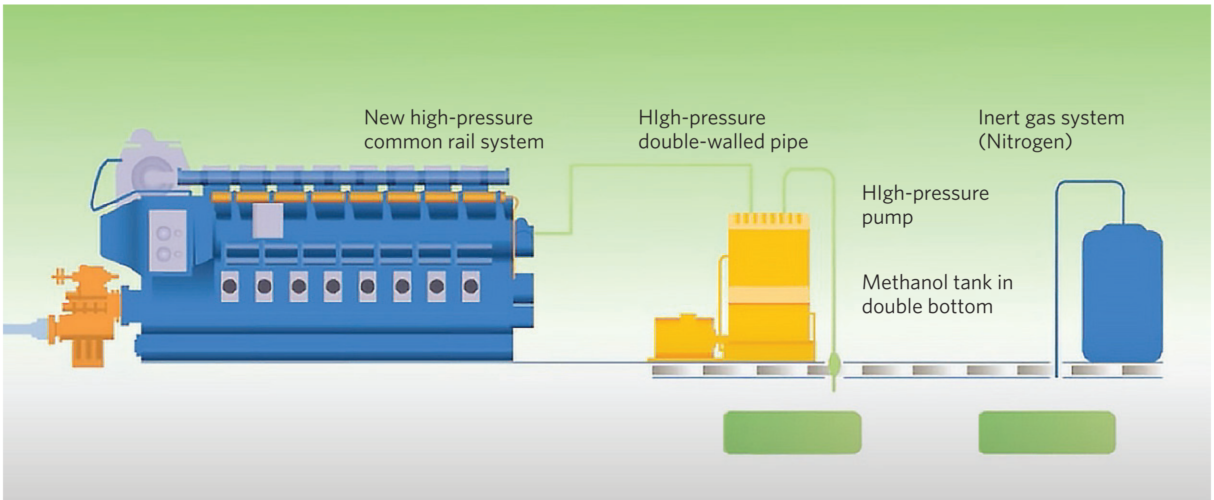
## 4.4 Stena Germanica's Conversion to Methanol Fuel

Stena Line is one of the world's largest ferry companies, with more than 25,000 yearly sailings. With headquarters in Gothenburg, Sweden, it employs more than 5,100 employees across Europe. In 2015, it became the first ferry operator to launch a methanol-fueled roll-on/roll-off passenger vessel, the Stena Germanica.

The dual-fuel cruise ferry, one of the largest in the world, operates between Gothenburg and Kiel and its conversion was a joint project by Stena Line and the two port authorities, along with Methanex Corporation and engine maker Wärtsilä. Stena Germanica's conversion involved the installation of a common rail system of fuel injection used in marine diesel engines, with a pressure pump and double-walled, high-pressure pipes.

The conversion was prompted by concern for compliance with sulfur regulations in Northern Europe, according to Ron Gerlach, Technical Director at Stena Teknik, a technical resource for Stena's maritime-related business units. "We had to come up with a solution to reduce sulfur emissions from our vessels dramatically, and methanol was one of them," he says. "It reduces sulfur to almost zero, and that was one of the preferred choices for us at the time."

**Figure 54. Schematics of a Dual-Fuel Engine and Fuel System**




Stena Germanica's conversion was so ahead of its time that "regulations were very much written alongside the research and development phase," Gerlach says.

Nevertheless, the conversion process was "relatively straightforward," he says. "We had to deal with some initial hiccups, but actually it was very smooth."

The performance of the dual-engine vessel has been entirely satisfactory, he says. Emissions consist mostly of water vapor and carbon dioxide. Sulfur and particulates have been reduced by 90 percent and nitrogen emissions by 60 percent.[67] The main challenge for the project has been in finding methanol supplies at commercially viable rates. "It all comes down to commercial agreements with methanol suppliers," Gerlach says.

"The key is of course to have a supply lined up, to have hubs where you bunker methanol," he says. "This is something that needs to be looked at jointly: where do you operate and then where do you have your supply lined up?"

Although the commercial viability of methanol is improving, Gerlach says, a growing issue may be where to acquire low-carbon supplies of the fuel. "Now, sulfur regulations are day-to-day business," he notes.

Low-carbon methanol can help vessel operators meet decarbonization targets but to do this they need to know what version of fuel—gray, blue or green—they can secure through commercial agreements. Furthermore, says Gerlach, securing methanol supplies might be easier for ferry services because the routes, timetables and bunker intervals are established well in advance. "When you enter the deep-sea shipping routes, that becomes more complicated," he says.

Ultimately, however, Stena Line views methanol as an attractive transition fuel for low-carbon operations because the progression from gray to green supplies offers a smooth route to decarbonization without requiring major changes to vessel design and operations. "Methanol still has carbon atoms in its structure, so we have to find ways, with carbon capture, to make it a truly sustainable fuel," he says.

67 Stena Line. (2021, March 31). The world´s first methanol ferry. Retrieved November 19, 2022, from stenaline.com: https://www.stenaline.com/media/stories/the-worlds-first-methanol-ferry

# 5.
# What is Next for Marine Methanol?

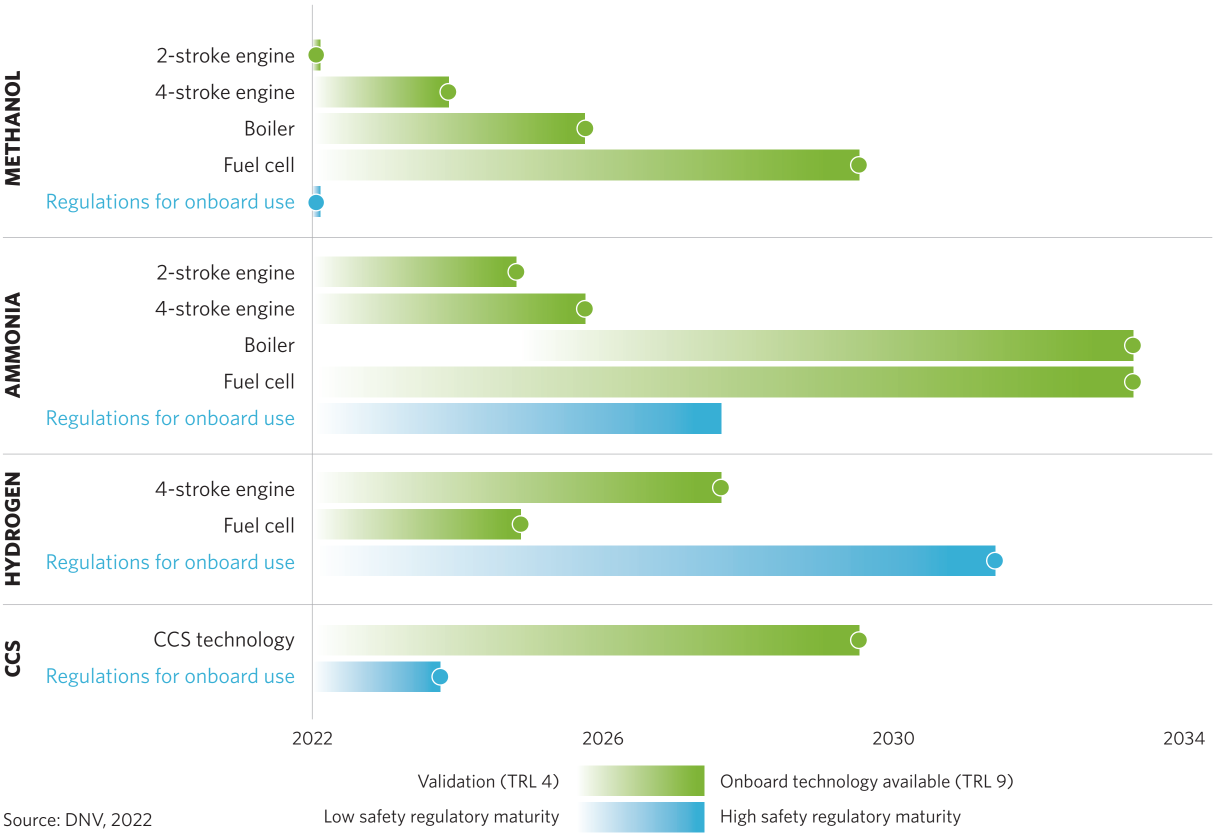
An increasing number of shipping companies are relying on marine methanol to navigate the transition toward net-zero shipping, including AP Moller Maersk, Methanex Waterfront Shipping, Stena, CMA CGM, COSCO and many more. A list of methanol ready vessels can be found here: Methanol Vessels on the Water and on the Way.

On the regulatory front, marine methanol meets the most stringent regulations issued by the IMO on $SO_X$, $NO_X$, and PM emissions. Additionally, marine methanol offers a clear pathway to minimizing carbon emissions, as operators switch from fossil fuels to carbon neutral e-methanol and bio-methanol.

The commercial availability of engines and fuel injection systems play in marine methanol's favor, as does the fact safety regulations for on-board use have already been developed. In this regard, marine methanol has the advantage of being ready to deploy today, unlike cryogenic fuels for which key technology and safety regulations are yet to be developed.

Methanol is a liquid at ambient temperature and pressure, making it easier to handle than cryogenic fuels. For this reason, methanol can be transported, stored and bunkered following procedures similar to those required by diesel fuels. The infrastructure used for marine fuels such as HFO and MGO can, with minor modifications, be used for methanol.

**Figure 55. Expected Availability of Alternative Marine Fuel Technologies - DNV Estimates**




Source: DNV, 2022

By virtue of being fully miscible in water and biodegradable, a methanol spill is likely to have only temporary and fully reversible effects on marine life. Other things being equal, you would need to spill 200 times more methanol than HFO to kill the same number of fish.

Shipping operators would have no problem sourcing methanol, as it is a globally traded commodity found in over 120 ports and produced in over 90 facilities with an aggregate production capacity of ~120 million tons. By 2050, production capacity is expected to grow to 500 million tons, out of which 80 percent will be ultra-low carbon e-methanol or bio-methanol, according to IRENA.

Regarding cost-effectiveness, a recent study has estimated that e-methanol and bio-methanol are the most cost-effective low carbon fuels by total cost of ownership. However, low carbon fuels are two to eight times more expensive than their fossil counterparts. This highlights the need for regulatory measures to encourage the widespread uptake of low carbon marine fuels, including e-methanol and bio-methanol.

# 5. References


ABS. (2021). *Methanol as a Marine Fuel: Sustainability Whitepaper.* ABS. Retrieved November 19, 2022, from https://safety4sea.com/wp-content/uploads/2021/02/Sustainability-Methanol-as-Marine-Fuel.pdf

Baresic, D., Rojon, I., Shaw, A., & Rehmatulla, N. (2022). *Closing the Gap: An Overview of the Policy Options to Close the Competitiveness Gap and Enable an Equitable Zero-Emission Fuel in Shipping.* London: University Maritime Advisory Service (UMAS). Retrieved June 7, 2022, from https://www.u-mas.co.uk/wp-content/uploads/2022/01/Closing-the-Gap_Getting-to-Zero-Coalition-report.pdf

Blue World. (n.d.). *Market Applications: Maritime*. Retrieved November 19, 2022, from Blue World Technologies: https://www.blue.world/markets/maritime/

Brynolf, S., Grahn, R., Korberg, A., & Skov, I. (2021, May). Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. *Renewable and Sustainable Energy Reviews, 142*. doi: https://doi.org/10.1016/j.rser.2021.110861

Buitendijk, M. (2020, March 10). *Waterfront Shipping: 'Methanol as a marine fuel works'*. Retrieved November 19, 2022, from SWZ Maritime: https://swzmaritime.nl/news/2020/03/10/waterfront-shipping-methanol-as-a-marine-fuel-works/

Bureau Veritas (2022, September). Alternative Fuels Outlook for Shipping: An Overview of Alternative Fuels from a Well-to-Wake Perspective. Retrieved March 3 from https://marine-offshore.bureauveritas.com/newsroom/alternative-fuels-outlook-shipping

Campbell, M., Davies, A., MacLean, G., Martin, C., Raugei, M., & Scammell, H. (2021). *Report for the Study on Sustainability Criteria and Life Cycle GHG Emission Assessment Methods and Standards for Alternative Marine Fuels.* Ricardo Energy & Environment. Retrieved June 12, 2022, from https://greenvoyage2050.imo.org/wp-content/uploads/2022/01/RicardoED_IMOAlternativeFuels_ReportFinal.pdf

*CII - Carbon Intensity Indicator.* (n.d.). Retrieved May 7, 2022, from DNV: https://www.dnv.com/maritime/insights/topics/CII-carbon-intensity-indicator/index.html

Concawe. (2019, March). A look into the maximum potential availability and demand for low-carbon feedstocks/fuels in Europe (2020–2050) (literature review). *Concawe Review, 27*(2).

Corner & Sathiamoorthy (2022) How updating IMO regulations can promote lower greenhouse gas emissions from ships (ICCT WORKING PAPER 2022-34), *International Council on Green Transportation.* Retrieved February 7, 2023, from https://theicct.org/publication/marine-imo-eedi-oct22/

Danelec. *The relation between EEXI, EEDI and Shaft Power Limiters* (n.d.). Retrieved February 2, 2023, from Danelec: https://www.danelec.com/insights/blog/the-relation-between-eexi-eedi-and-shaft-power-limiters/

DNV. (2020, July 23). *Achieving the IMO decarbonization goals.* Retrieved May 31, 2022, from DNV: https://www.dnv.com/expert-story/maritime-impact/How-newbuilds-can-comply-with-IMOs-2030-CO2-reduction-targets.html

*EEXI – Energy Efficiency Existing Ship Index.* (n.d.). Retrieved May 7, 2022, from Lloyd's Register: https://www.lr.org/en/eexi-energy-efficiency-existing-ship-index/

Fastwater. (2021). *Report on methanol supply, bunkering guidelines, and infrastructure.* Fastwater. Retrieved November 21, 2022, from https://www.fastwater.eu/images/fastwater/news/FASTWATER_D71.pdf

Forsyth, A. (2022, January 25). All At Sea - Methanol and Shipping. Retrieved May 2, 2022, from https://www.proman.org/wp-content/uploads/2022/01/Methanol-and-Shipping-2501221.pdf

Forster, P., V. Ramaswamy, P. Artaxo, T. Berntsen, R. Betts, D.W. Fahey, J. Haywood, J. Lean, D.C. Lowe, G. Myhre, J. Nganga, R. Prinn, G. Raga, M. Schulz and R. Van Dorland (2007). Changes in Atmospheric Constituents and in Radiative Forcing. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge UniversityPress, Cambridge, United Kingdom and New York, NY, USA. Retrieved June 12, 2022, from www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter2.pdf

Grainger, T. (n.d.). *Shipping companies are taking a new look at scrubbers*. Retrieved November 19, 2022, from Pacific Green: https://www.pacificgreen-group.com/articles/shipping-companies-are-taking-new-look-scrubbers/

Green Maritime Methanol. (2021, February 19). *Green Maritime Methanol - Towards a Zero Emission Shipping Industry.* Retrieved June 12, 2022, from Green Maritime Methanol: http://resolver.tudelft.nl/uuid:0542ccdc-00fc-4229-a39f-401688d3ee03

GreyViews. (2022, Jan). *Global Marine Engines Market Overview*. Retrieved November 19, 2022, from greyviews.com: https://greyviews.com/reports/global-marine-engines-market/17

Hamelinck, C., & Bunse, M. (2022, February 4). *The carbon footprint of methanol produced from various feedstocks.* Retrieved June 12, 2022, from Studio Gear Up: https://www.studiogearup.com/the-carbon-footprint-of-methanol-produced-from-various-feedstocks/

Heinrich-Böll-Stiftung European Union. (2021, February 3). *Shipping: Setting Sail - Challenges for Sea Transport*. (N. Sifakis, & P. T. Tsoutsos, Editors) Retrieved May 29, 2022, from Heinrich-Böll-Stiftung European Union: https://eu.boell.org/en/shipping-setting-sail-challenges-for-sea-transport

*Initial IMO GHG Strategy.* (n.d.). Retrieved May 7, 2022, from International Maritime Organization: https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx

International Energy Agency. (2022, September). *Direct Air Capture*. Retrieved November 19, 2022, from iea.org: https://www.iea.org/reports/direct-air-capture

International Energy Agency. (2022, September). *Hydrogen*. Retrieved December 11, 2022 from iea.org: https://www.iea.org/reports/hydrogen

International Energy Agency. (2022, March). *Global Energy Review: $CO_2$ Emissions in 2021.* Retrieved November 19, 2022, from iea.org: https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2

International Martime Organization (IMO). (2022, May 24). *ISWG-GHG 12: Reducing GHG Emissions from Ships.* Retrieved June 12, 2022, from imo.org: https://www.imo.org/en/MediaCentre/PressBriefings/pages/ISWGHGMay2022.aspx

IRENA. (2021). *A pathway to decarbonise the shipping sector by 2050.* Abu Dhabi: International Renewable Energy Agency. Retrieved November 19, 2022, from https://irena.org/publications/2021/Oct/A-Pathway-to-Decarbonise-the-Shipping-Sector-by-2050

IRENA and Methanol Institute. (2021). *Innovation Outlook: Renewable Methanol.* Abu Dhabi: International Renewable Energy Agency. Retrieved June 19, 2022, from https://www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol

Joint Research Centre - European Commission (2017, July) Definition of input data to assess GHG default emissions from biofuels in EU legislation – Version 1 C. Retrieved on September 15, 2022, from https://op.europa.eu/en/publication-detail/-/publication/f95536ce-6cf8-11e7-b2f2-01aa75ed71a1/language-en

Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. (2021, October). *We show the world it is possible.* Retrieved May 2, 2022, from Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping: https://cms.zerocarbonshipping.com/media/uploads/documents/MMMCZCS_Industry-Transition-Strategy_Oct_2021.pdf

MAN Energy Solutions. (2020, March 30). Market Update Note: Introducing the LGIM-W principle. Retrieved June 12, 2022, from https://man-es.com/docs/default-source/marine/tools/introducing-the-lgim-w-principle.pdf?sfvrsn=a128e177_8

MAN Energy Solutions. (2021, July 19). Methanol ExpertTalk Shipowner. Retrieved November 19, 2022, from https://www.youtube.com/watch?v=Ftxnn-4dqoM&t=367s.

MAN Energy Solutions. (2021, July 19). Methanol ExpertTalk Shipowner and Charterer. Retrieved November 19, 2022, from https://www.youtube.com/watch?v=_mCkvOr2dDU&t=109s

MAN Energy Solutions. (2022). *Methanol for the maritime energy transition*. Retrieved November 19, 2022, from MAN Energy Solutions: https://www.man-es.com/marine/strategic-expertise/future-fuels/methanol

Marine Service Noord. (n.d.). *Case study MV Eemsborg*. Retrieved November 19, 2022, from Marine Service Noord: https://marine-service-noord.com/en/products/alternative-fuels-and-technologies/methanol/case-study-mv-eemsborg/

Marine Service Noord. (n.d.). *Two concepts for methanol fuel systems*. Retrieved November 19, 2022, from Marine Service Noord: https://marine-service-noord.com/en/products/alternative-fuels-and-technologies/methanol/two-concepts-for-methanol-fuel-systems/

Muchira, N. (2022, May 27). *IMO Breaks Deadlock on Carbon Pricing for Shipping*. Retrieved May 29, 2022, from The Martime Executive: https://www.maritime-executive.com/article/imo-breaks-deadlock-on-carbon-pricing-for-shipping

*Nitrogen Oxides (NOx) – Regulation 13.* (n.d.). Retrieved May 7, 2022, from International Maritime Organization: https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NOx)-%E2%80%93-Regulation-13.aspx

Panoutsu, Calliope and Maniatis, Kyriakos (August 2021). Sustainable biomass available in the EU to 2050. Imperial College London Consultants for Concawe. Retrieved July 16 https://www.fuelseurope.eu/wp-content/uploads/Sustainable-Biomass-Availability-in-the-EU-Part-I-and-II-final-version.pdf

Pape, M. (2021, November 8). *Sustainable maritime fuels.* Retrieved May 10, 2022, from European Parliament: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698808/EPRS_BRI(2021)698808_EN.pdf

Prussi, M., Panoutsou, C., & Chiaramonti, D. (2022, January 12). Assessment of the Feedstock Availability for Covering EU Alternative Fuels Demand. (T. Yusaf, Ed.) *Applied Sciences, 12*(740). doi:https://doi.org/10.3390/app12020740

Smith, A. S. (2022). *An overview of the discussions from IMO SWG-GHG 12.* UMAS. Retrieved May 29, 2022, from https://www.u-mas.co.uk/wp-content/uploads/2022/05/ISWG-GHG-overview-UMAS-final.pdf

Stena Line. (2021, March 31). *The world´s first methanol ferry*. Retrieved November 19, 2022, from stenaline.com: https://www.stenaline.com/media/stories/the-worlds-first-methanol-ferry/

The Maritime Executive. (2021, May 12). *World's First Barge Bunkering with Methanol Demonstrates Potential*. Retrieved November 21, 2022, from The Maritime Executive: https://maritime-executive.com/article/world-s-first-barge-bunkering-with-methanol-demonstrates-potential

*The Methanol Industry.* (2022). Retrieved May 2, 2022, from Methanol Institute: https://www.methanol.org/the-methanol-industry/

Wankhede, A. (2021, April 2021). *Why 2-stroke Engines are Used More commonly than 4-stroke on Ships?* Retrieved November 19, 2022, from Marine Insight: https://www.marineinsight.com/main-engine/why-2-stroke-engines-are-used-more-commonly-than-4-stroke-on-ships/

Xiaodong, Z. (2022, April). Shipping Efficiency Game 2023 -2030. Lloyd's Register. Retrieved May 05, 2022

Zomer, G., Finner, S., Harmsen, J., Vredeveldt, L., & van Lieshout, P. (2020). *Green Maritime Methanol: Operation aspects and the fuel supply chain.* The Hague: TNO. Retrieved November 19, 2022, from https://publications.tno.nl/publication/34637282/W1qAlG/TNO-2020-R11105.pdf