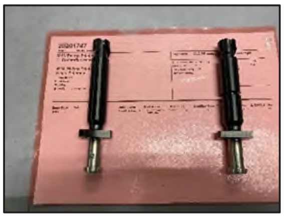
Task Number 60

**A Report from the**
**Advanced Motor Fuels Technology Collaboration Programme**




# Task 60:
# The Progress of Advanced Marine Fuels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# Summary / Abstract

Significant progress has been made in recent years to adapt marine power systems to future low-carbon and carbon free fuels. This report showcases international achievements and ongoing efforts to adapt combustion engines to the fuels of the future.

Some main conclusions of this report are:

Marine engine technology can utilize a wide range of renewable fuels and the market for flexible fuel marine engines is steadily growing.

The main fuels in focus currently are LNG, LPG, Methanol, Ammonia, Pyrolysis-oils, Bio-crudes, and Hydrogen.

Marine engines are available as gasoline-type SI-engines up to ~10 MW, 4-stroke diesels up to ~20 MW and 2-stroke diesels up to ~80 MW.

The dominant engine technology for alternative fuel use is Dual Fuel Technology.

Dual Fuel engines with low pressure gas admission deliver environmental benefits due to low $NO_X$ emissions compliant with IMO Tier III without aftertreatment. Any other engine type can be equipped with SCR and/or EGR to enable compliant $NO_X$ emissions.

Sulfur emissions can be tackled with the new standard LSFO fuel, available since 2020, or with a scrubber installation.

Particle emissions, especially Black Carbon emissions, are most effectively reduced using clean burning fuels such as gas or alcohol. Scrubbers alone do not always solve this in full, and particulate filters are not suitable for every engine.

$CO_2$ emissions from engines are most effectively reduced with renewable Power-to-X-type fuels, or advanced biofuels. On-board Carbon capture is a technology under investigation. Carbon Capture can be combined with bio- or Power-to-X-fuels for maximum impact. Ammonia and hydrogen are entirely carbon free fuels that do not emit $CO_2$.

# Contents

## List of Tables

## List of Figures

# Introduction

In 2013 AMF released its first annex report on marine fuels (Annex 41). This report highlighted the fact that no alternative fuel option existed without significant added cost or other serious impediments. Even the preferred fuel, HFO, was soon to be banned or restricted due to the high sulfur and fossil carbon content.

Recently, however, several new fuel options have gained attention.

This report is established to create an assessment of fuel options that have emerged or significantly developed since the 2013 report (AMF Annex 41). The outcome that participants wish to achieve is a better understanding of the potential and limitations of new marine fuel options. The key question that we wish to address is “How can the new forms of advanced marine fuels contribute to carbon neutral shipping in the future?”

Advanced marine fuels include, but are not limited to, LNG/LEG/LBG, Methanol, Ammonia, Hydrogen, and biodiesel.

The participants have independently worked on their contributions and submitted their findings. Each participant has presented their work program and progress at least once during the project, in a teleconference arranged by the operating agent.

The operating agent, Danish Technological Institute, has compiled the findings into this report, which has been reviewed by all participants.

The management of this Task was kindly co-financed by the Methanol Institute.

## Marine engine technology

*This section was written by DTI, Denmark.*

Most propulsion solutions for large commercial vessels today are based on shaft power from large 2-stroke and 4-stroke engines, with no current or near future feasible alternatives.

This chapter contains a brief overview of marine engine technology, which is useful in understanding the technical limitations and possibilities in relation to alternative fuels.

The chapter describes operating principles and main characteristics of marine engines, and the developments and adaptations that have enabled these engines to operate with new fuel types.

Other propulsion technologies, such as steam and gas turbines, are used in some ships, but these are not as energy efficient as large piston engines. The use of gas turbines today is mainly reserved for military vessels, in which the supreme power-to-weight/volume ratio is more important than fuel economy.

Steam turbines were previously installed mostly in LNG carriers, where they used boil-off gas for steam generation. The steam turbine technology was gradually replaced in new LNG carriers from year 2000 onwards, first by 4-stroke dual fuel and later 2-stroke dual fuel engines, which provide higher fuel efficiencies.

### Marine engine applications

Ships generally require power for propulsion (main engines), electricity generation (auxiliary engines) and emergency power generation.

Since the introduction of the diesel engine for marine propulsion, these power requirements have been handled by separate engine types and installations. This is still how many ships are constructed today, particularly in large ships, where large 2-stroke engines are preferred for propulsion due to their superior efficiency. Other propulsion principles have since been developed, e.g., diesel electric propulsion, and advanced waste heat recovery systems that utilize exhaust waste heat in steam turbines or Organic Rankine Cycles.

The engine technology itself has also been developed to accommodate new fuel types. This development is largely motivated by customers' demand for alternative fuel capability.

The largest recent changes to engines are related to the combustion principles, which are used to ensure combustion of fuel with different physical and thermochemical properties than diesel. The relation between engine technology and applicable combustion principles will be clarified in the following sections.

### Specification of engines

The power of a marine engine is usually expressed as MCR (Maximum Continuous Rating) in Megawatts (MW). Smaller engines used for small commercial and recreational boats may be in the range of kilowatts (kW) or horsepower (hp), with 1 hp = 0.736 kW.

**Bore** is the internal diameter of the cylinder, usually measured in cm for large bores. Most engine designations refer to bore size.

**Stroke** is the vertical travel distance of the piston in the cylinder. It will in most cases be larger than the bore, to make the engine more energy efficient.

**The mean effective pressure (MEP)** indicates the relation between the usable work per cycle and the displacement volume. This allows direct comparison of engines of different sizes and at different speeds.

The MEP is calculated as:

$$MEP\ [bar] = \frac{n\ \times\ 60 \times power\ [MW]}{displacement\ volume\ [m^3] \times engine\ speed\ [min^{-1}]} \times \frac{1 \times 10^6\ W}{MW} \times \frac{1\ bar}{1 \times 10^5\ pa}$$

$$= \frac{n\ x\ 2\pi \times torque[Nm]}{displacement\ volume\ [m^3]} \times \frac{1\ bar}{1 \times 10^5\ pa}$$

In this equation, n is the number of revolutions per combustion cycle; 2 for 4-stroke engines and 1 for 2-stroke engines.

## 2-stroke engines

2-stroke marine engines are generally very large engines, that are designed for continuous operation for the lifetime of the ship. The engines are available in a large range of power, for propulsion of ships of varying size. As example, Table 1 shows the largest and smallest monofuel 2-stroke engines available from MAN Energy Solutions (MAN ES) and WinGD, which are the leading 2-stroke engine designers.

*Table 1 Smallest and largest 2-stroke engines available today*

| Engine designation | Bore [cm] | Stroke [cm] | Cylinders [number] | Power [MW] | MEP [Bar] | Speed [RPM] |
|---|---|---|---|---|---|---|
| MAN B&W G95ME-C10.6 | 95 | 346 | 6 - 12 | 41 - 82 | 21 | 70 - 80 |
| MAN B&W S30ME-B9.5 | 30 | 133 | 5 - 8 | 3 - 5 | 21 | 148 - 195 |
| WinGD X-92B | 92 | 347 | 6-12 | 24 - 77 | 21 | 70-80 |
| WinGD X-35B | 35 | 155 | 5-8 | 2.5 - 7 | 21 | 118-167 |

These engines are exclusively used as main engines for propulsion on large vessels, with a direct propeller drive through a fixed shaft. The shaft does not use gearing, so the propeller turns at the same speed as the engine. Reversing is performed by stopping the engine and then running it in the opposite direction. Most ships have a single centrally placed 2-stroke engine, but some of the large container ships and most LNG carriers are equipped with smaller twin engines and propellers.

The 2 -stroke operating principle means that the engine is burning fuel with every revolution and scavenging the cylinder with fresh combustion air is performed while the piston is in bottom position in the cylinder. This means that these engines provide constant high torque at low operating speed, which is suitable for propulsion with large diameter propellers.

### 2-stroke Dual-fuel engines

2-stroke engines were originally designed for use only with fuel oil to be injected at high pressure through multiple injectors into each cylinder. Due to increasing demands and availability of new fuel types, the injection technology of those engines has now been further developed to allow the use of alternative fuels, with natural gas (NG) being the most common. Many of the existing engine models developed for diesel are therefore also now available in Dual Fuel (DF) versions, and ships in operation can in some cases be retrofitted for DF operation with NG.

LNG (Liquified Natural Gas) is the most common alternative to fuel oil. In 2023 it is used in dual fuel propulsion and auxiliary engines on approx. 1100 ships of different types and sizes, of which 668 are active LNG carriers.

LPG (Liquified Petroleum Gas) and LEG (Liquified Ethane Gas) are used in dual fuel engines on gas carriers transporting these gases. In 2023, LPG is used on 77 gas carriers, and LEG on 19 gas carriers.

Dual fuel engines use three different injection technologies: High pressure gas injection for LNG and LEG, high pressure liquid fuel injection for LPG and methanol, and low-pressure gas admission for LNG.

### 2-stroke Dual-fuel engines with high-pressure injection

In the high-pressure gas and liquid injection concepts used in MAN DF engine variants, dedicated fuel injectors are used to inject the alternative fuels into the cylinder, while standard fuel oil injectors inject marine fuel oil to provide ignition for the alternative fuels. In this combustion principle, combustion of the gas occurs like in diesel engines, with diffusion flame combustion. The combustion of gas generally leads to very low formation of particulate matter, but $NO_x$ formation is still relatively high and requires $NO_x$ control to comply with IMO Tier III. MAN ES currently offers several types of dual fuel 2-stroke engines for three types of gas fuels, as shown in Table 2.

*Table 2* MAN ES engine variants for alternative fuels

| Fuel type | Fueling principle | Designation | Combustion principle |
|---|---|---|---|
| LNG<br>LEG | High pressure gas injection | GI<br>GIE | Diesel combustion process with ignition by fuel oil pilot injection |
| Methanol<br>LPG | High pressure liquid injection | LGIM<br>LGIP | Diesel combustion process with ignition by fuel oil pilot injection |
| LNG | Low pressure gas admission | GA | Otto process with ignition by fuel oil pilot injection |

### 2-stroke Dual-fuel engines with low-pressure injection

In low pressure DF engines, gas is supplied at low pressure, with injection through separate valves in the bottom part of the cylinder liner. The gas mixes with the combustion air to form a highly premixed combustion at TDC, which reduces $NO_x$ and particulate formation. The low-pressure DF engine types comply with IMO Tier III in combination with EGR only. The low-pressure solution reduces the complexity and price of the fuel system, which is designed for a low operating pressure.

WinGD has been offering the low pressure 2-stroke Otto cycle combustion concept with their X-DF engine models since 2013. MAN ES launched a similar engine type designated GA (Gas Admission) in 2021.

### Low speed Dual-Fuel engines for large ships

*This section was written by WinGD, Switzerland.*

In contrast to the projections made in AMF Annex 41, the application of natural gas in the shipping sector has gained considerable momentum and LNG has become a viable option for a large range of vessel types and trades. Back then, natural gas was expected to account for a share of no more than 1% (2.4 MT) of the total fuel used in global shipping by 2020. In reality, the LNG portion of the fuel used in shipping in 2020 amounted to almost 12 MT, which corresponded to a share of 5.9% of the total reported 203 million tons of fuel consumed (IMO, 2020).

This significantly faster adoption of LNG as marine fuel was facilitated by two main developments:

1. LNG supply infrastructure has been expanded considerably and additional bunkering facilities continue to be built, specifically along the main trade routes. Figure 1shows the status of LNG terminals in place in 2020.
2. Dual-fuel technologies have been further developed and rolled out across a large range of marine engine types and sizes, specifically including the (two-stroke) propulsion engines used in international merchant shipping.


*Figure 1 Status of LNG terminals availability 2020 (extracted from (SEA-LNG, 2022))*

In this large two-stroke engine segment, two technological approaches have been brought to the market by the two main players:

The ME-GI gas injection concept devised by MAN Energy Solutions (MAN-ES) was already briefly introduced in the AMF Annex 41. Its main features consist in the diesel-type combustion of gas jets, which are injected into the combustion chamber of each cylinder around the end of the compression stroke, via dedicated gas injectors in a way similar to typical diesel fuel sprays; however, applying lower injection pressures in the range of 150 to 315 bar, depending on engine load. Ignition of these gas jets is achieved by injecting a small quantity of pilot fuel via the backup fuel system. The gas injector as the key element of this technology as well as the working principle of the concept in general are shown for illustration in Figure 2. Note that variants of the technology involving adjustments to the specific applications have been realized with the ME-GIE variant, which is capable of working with other gaseous fuels such as ethane and blends of LNG and VOC, and the liquid gas injection (LGI) technologies, in which specifically tailored solutions exist for liquified petroleum gas (LPG) and methanol, designated as ME-LGIP and ME-LGIM, respectively. The ME-GI solution has already been rolled out to engine sizes ranging from 350 mm to 950 mm bore, whereas the GIE, LGIP and LGIM variants are still limited to only a few engine sizes.

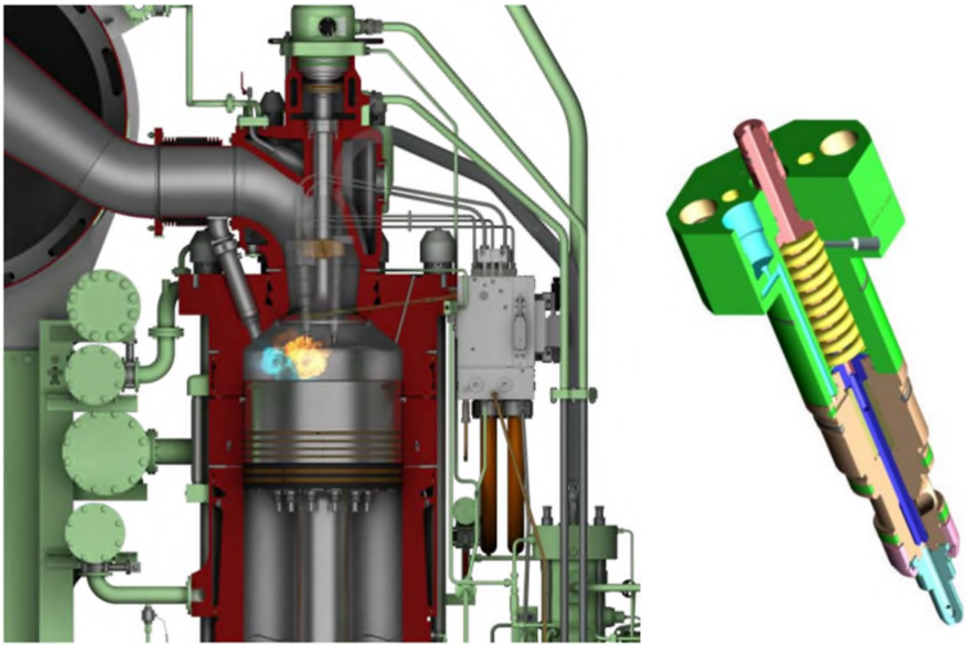

*Figure 2 Illustration of the ME-GI working principle* (left) and gas injector design (right) as key system feature *(Juliussen)*

The second technical approach consists in engines operating according to the Otto process, applying lean burn premixed combustion technology, as illustrated in Figure 3for the X-DF concept developed by Winterthur Gas & Diesel (WinGD). This concept is based on the admission of the gas to the cylinder, via gas admission valves located at about mid-stroke position in the cylinder liners. The gas is fed to those valves at relatively low pressure (below 15 bar) and then mixes with the scavenge air during the compression stroke, until the premixed charge is then ignited by means of hot jets emanating from (passive) pre-chambers, into which small quantities of pilot fuel are injected via a dedicated pilot fuel injection system. This concept has also proven to be applicable for blends of LNG and VOC. It is available across the WinGD product size range, from 400 mm to 920 mm bore engines. Recently, a largely similar approach has been developed by MAN-ES, specifically tailored for the engine size applicable in the LNG carrier segment (700 mm bore), which is designated as ME-GA.

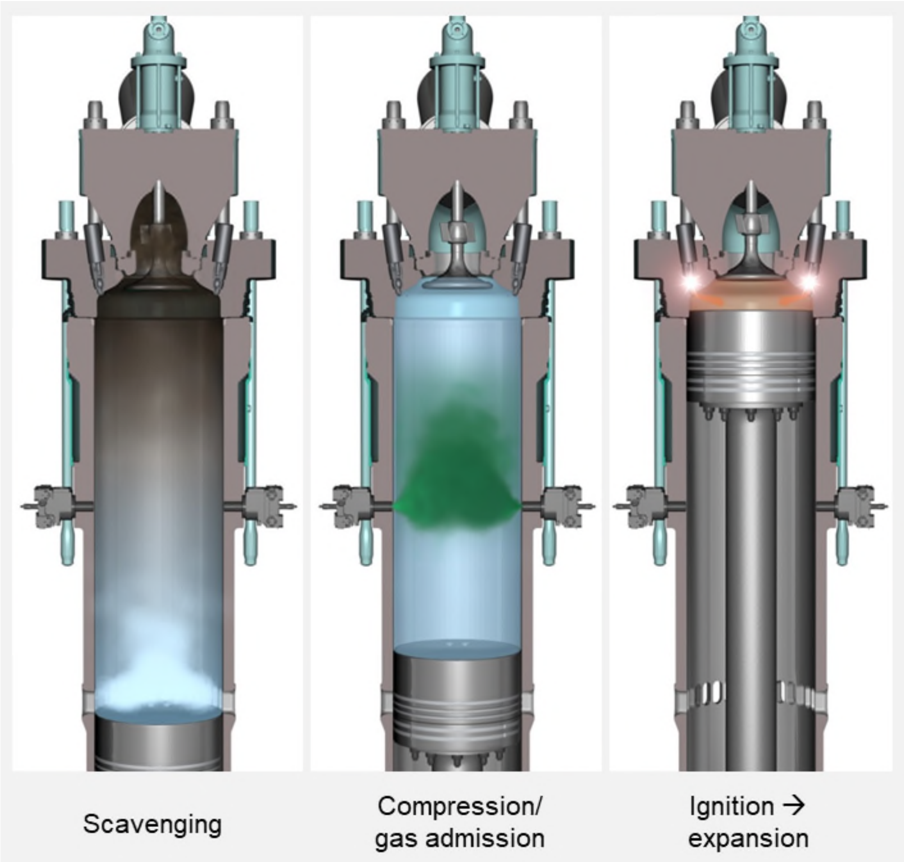


*Figure 3 Illustration of WinGD's X-DF working principle (Nylund, 2013)*

These dual-fuel technology developments also form the basis for the establishment of solutions for further fuels, specifically including carbon-reduced or even carbon-free and, ideally, completely renewable ones. Both major engine developers have announced rather ambitious plans to roll out methanol engine technology across the complete product range and develop ammonia engine technology for implementation in first products within the next three years.

The IMO GHG reduction strategy is based on the year 2008's $CO_2$ as 940 Mt of $CO_2$ and the same amount of GHG would be reduced by 2050 to achieve carbon neutrality. Due to this radical strategy, a variety of low carbon fuels are now under consideration to replace current heavy fuel oils. Since the strategy includes the existing ships and they are hard to be modified to adopt lighter fuel, a huge fuel transition is anticipated for newly building ships, and ammonia as well as hydrogen, which are called together as zero carbon fuel, are spotlighted to have an important role in the upcoming transition.

During the fuel transition from traditional marine fuel to zero carbon fuel, a variety of low carbon fuel including biofuel are to be investigated to meet short term regulation targets. Figure 5 shows a forecast of the fuels by which HIMSEN engine is going to be fueled according to the demand from stakeholders with regard to the marine fuel market.

| Fuel types | MC | ME-B | ME-C | ME-GI | ME-GA | ME-GIE | ME-LGIM | ME-LGIP |
|---|---|---|---|---|---|---|---|---|
| 0-0.50% S VLSFO | Design | Design | Design | Design | Design | Design | Design | Design |
| HFO | Design | Design | Design | Design | Design | Design | Design | Design |
| Biofuels | Design | Design | Design | Design | Design | Design | Design | Design |
| LNG | - | - | Retrofit | Design | Design | Retrofit | Retrofit | Retrofit |
| LEG (Ethane) | - | - | Retrofit | Retrofit | - | Design | Retrofit | Retrofit |
| Methanol / Ethanol | - | - | Retrofit | Retrofit | - | Retrofit | Design | Retrofit |
| LPG | - | - | Retrofit | Retrofit | - | Retrofit | Retrofit | Design |
| Ammonia | - | - | Retrofit | Retrofit | - | Retrofit | Retrofit | Retrofit |

| Fuel Type | Drop-in capable | X-engines | X-DF engines |
|---|---|---|---|
| 0 – 0.5%S VLSFO | n/a | Available | Available |
| HFO | n/a | Available | Available |
| Bio-diesel | ✓ | Available | Available |
| LNG | n/a | Retrofit | Available |
| Bio-methane | ✓ | Retrofit | Available |
| Synthetic methane | ✓ | Retrofit | Available |
| Ammonia | Dual- / Tri-Fuel | In Development | In Development |
| Methanol/ Ethanol | Dual- / Tri-Fuel | In Development | In Development |
| Lignin- derived biofuel | (✓) | Available | Available |

*Figure 4 Overview of fuel types and their applicability / retrofit ability on different engine design variants:* MAN-ES (top, *(Bidstrup, 2021)*), WinGD (bottom, *(Schneiter, 2021)*)

The third player in this market, Japan Engine Corporation (J-ENG), who is providing engines mainly for the Japanese domestic market and hence only accounts for a global market share in the low single-digit percentage range, has also announced its intention to look into future fuels. In contrast to the two main competitors, they intend to assess the feasibility of a hydrogen fueled large two-stroke engine directly, in the context of a collaborative R&D program with public funding (Japan Engine Corporation, 2021).

### Future 2-stroke multifuel engines

*This section was written by KSOE, Korea*

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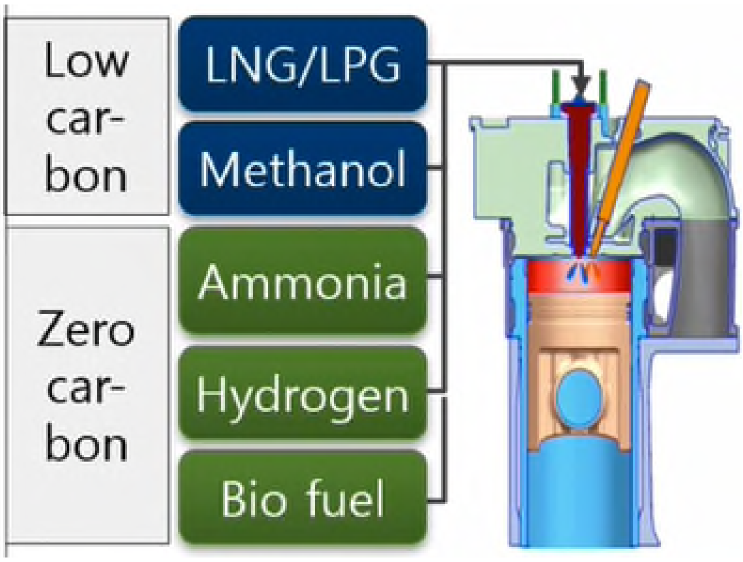



*Figure 5 HiMSEN multifuel engine (Korea)*

As an example of preparation for the fuel transitions, various low flash point fuel and ammonia were investigated to replace diesel in the compression ignition engine. For the experiments, 3L diesel engine was installed and gaseous fuels were supplied through pressure control valve then into the intake manifold.

Figure 6 to Figure 8 show the combustion results from ammonia-CNG-diesel triple fuels. Both ammonia and CNG was supplied via pressure control valve installed in the intake valve and the fuels were supplied into the cylinder in the intake process with fresh air.

With increasing CNG portion, the triple fuel combustion showed better fuel consumptions but slight increase in $NO_X$ emissions and $CO_2$ emissions. However, unburned ammonia was reduced with tolerable range and better fuel consumption as well.

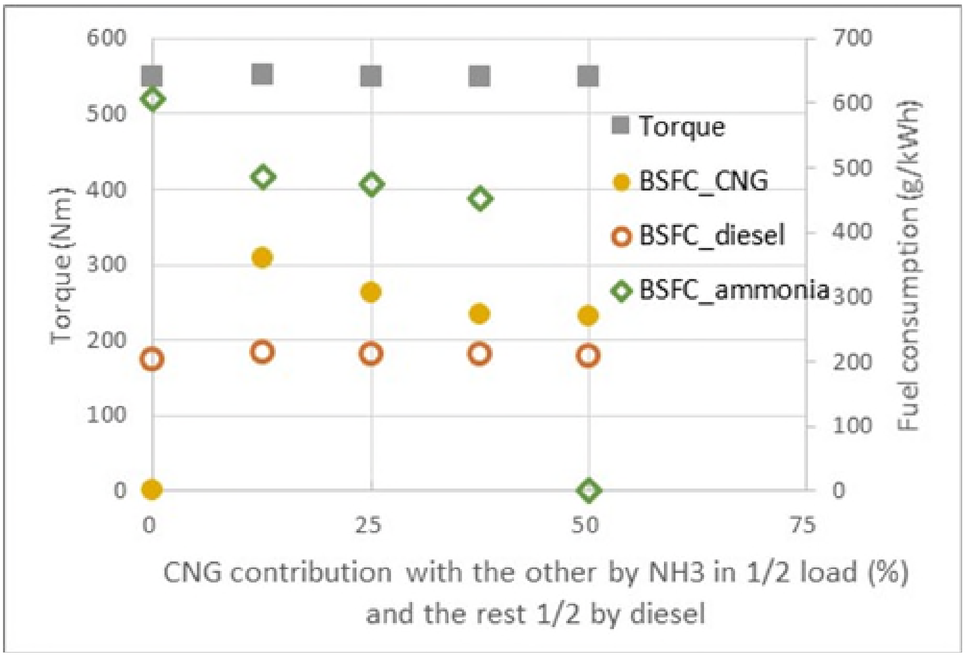



*Figure 6 Torque output and brake specific fuel consumption with ammonia-CNG-diesel triple fuel combustion at full load condition.*

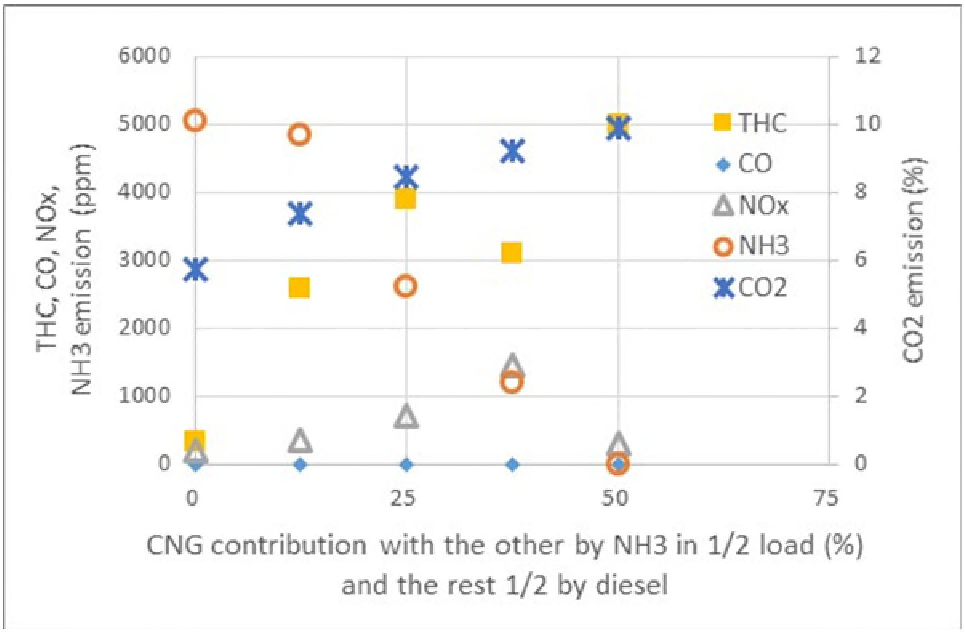



*Figure 7 Emissions from ammonia-CNG-diesel triple fuel combustion at full load condition*

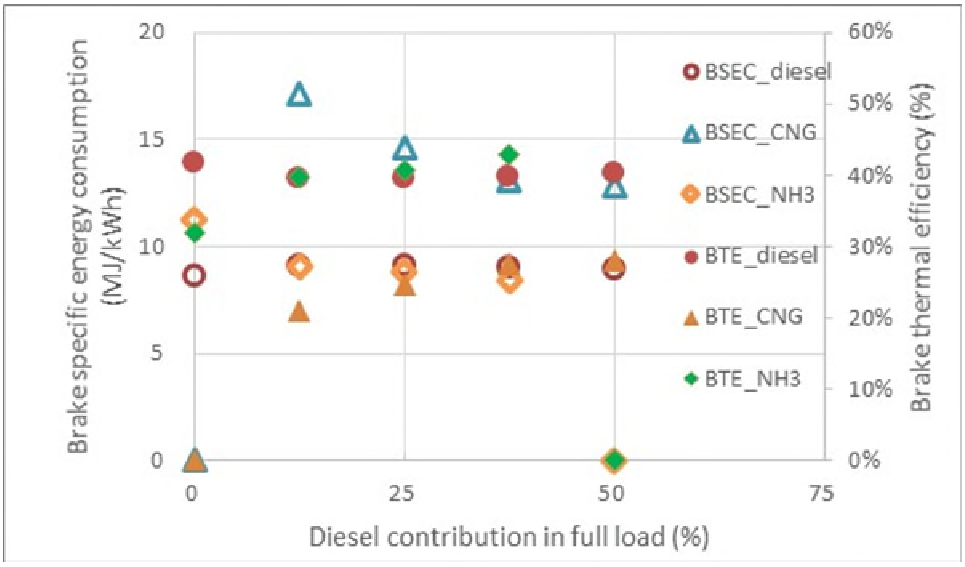



*Figure 8 Brake specific energy consumptions and thermal efficiencies from ammonia-CNG-diesel triple fuel combustion at full load condition.*

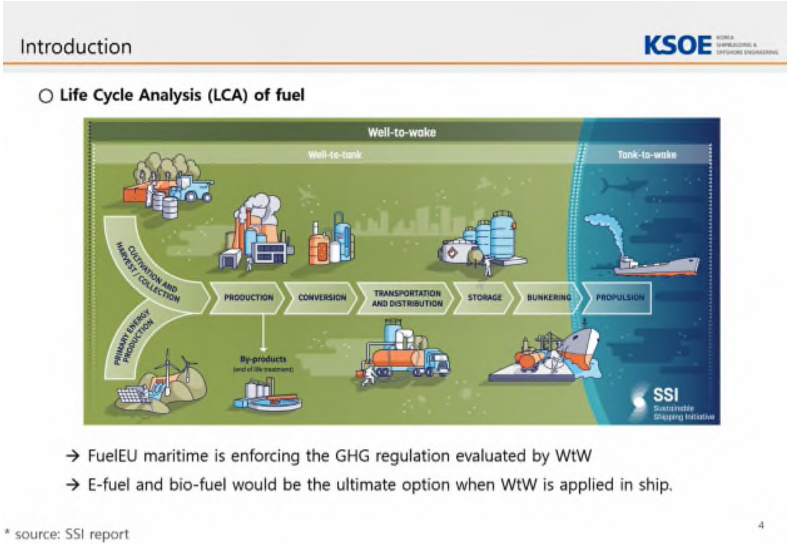



*Figure 9 Scope of marine fuel LCA.*

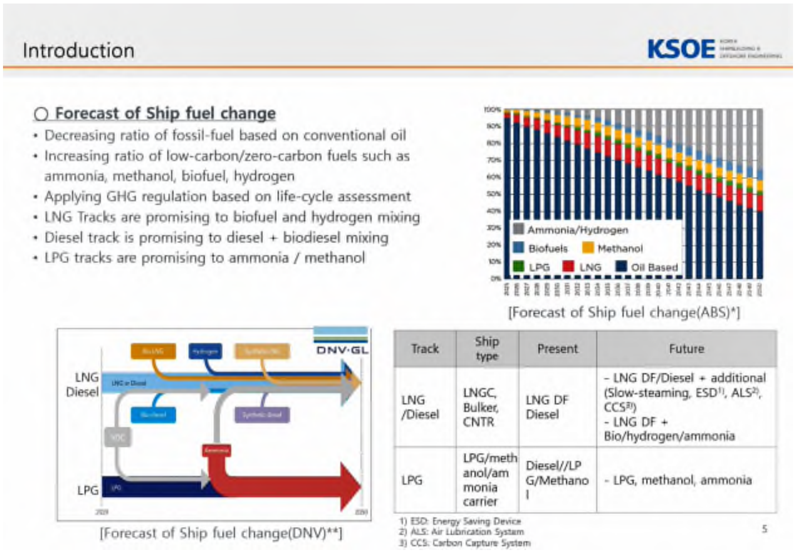
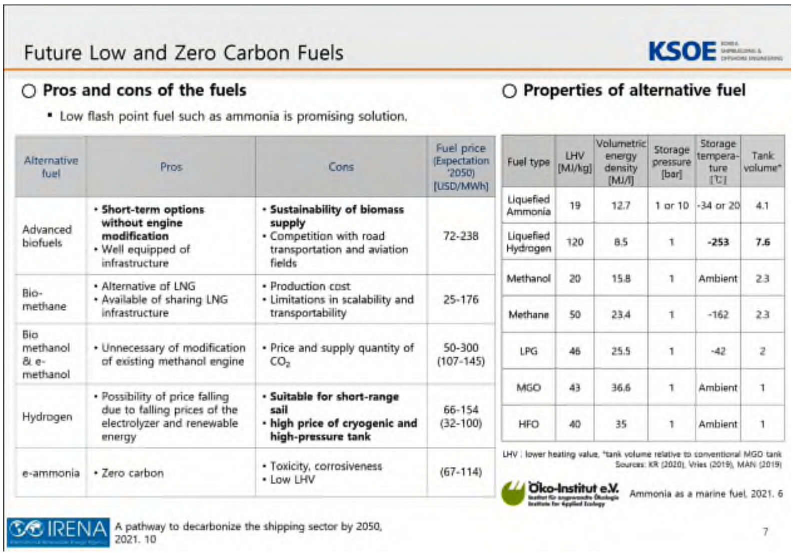



*Figure 10 Forecast of marine fuel changes.*


*Figure 11 Current state of ship building for advanced fuels.*



Future Low and Zero Carbon Fuels

○ **Pros and cons of the fuels**

- Low flash point fuel such as ammonia is promising solution.

| Alternative fuel | Pros | Cons | Fuel price (Expectation '2050) [USD/MWh] |
|---|---|---|---|
| Advanced biofuels | • **Short-term options without engine modification**<br>• Well equipped of infrastructure | • **Sustainability of biomass supply**<br>• Competition with road transportation and aviation fields | 72-238 |
| Bio-methane | • Alternative of LNG<br>• Available of sharing LNG infrastructure | • Production cost<br>• Limitations in scalability and transportability | 25-176 |
| Bio methanol & e-methanol | • Unnecessary of modification of existing methanol engine | • Price and supply quantity of $CO_2$ | 50-300 (107-145) |
| Hydrogen | • Possibility of price falling due to falling prices of the electrolyzer and renewable energy | • **Suitable for short-range sail**<br>• **high price of cryogenic and high-pressure tank** | 66-154 (32-100) |
| e-ammonia | • Zero carbon | • Toxicity, corrosiveness<br>• Low LHV | (67-114) |

IRENA A pathway to decarbonize the shipping sector by 2050, 2021. 10

○ **Properties of alternative fuel**

| Fuel type | LHV [MJ/kg] | Volumetric energy density [MJ/l] | Storage pressure [bar] | Storage tempera-ture [℃] | Tank volume* |
|---|---|---|---|---|---|
| Liquefied Ammonia | 19 | 12.7 | 1 or 10 | -34 or 20 | 4.1 |
| Liquefied Hydrogen | 120 | 8.5 | 1 | **-253** | **7.6** |
| Methanol | 20 | 15.8 | 1 | Ambient | 2.3 |
| Methane | 50 | 23.4 | 1 | -162 | 2.3 |
| LPG | 46 | 25.5 | 1 | -42 | 2 |
| MGO | 43 | 36.6 | 1 | Ambient | 1 |
| HFO | 40 | 35 | 1 | Ambient | 1 |

LHV : lower heating value, *tank volume relative to conventional MGO tank
Sources: KR (2020), Vries (2019), MAN (2019)

Öko-Institut e.V. Ammonia as a marine fuel, 2021. 6

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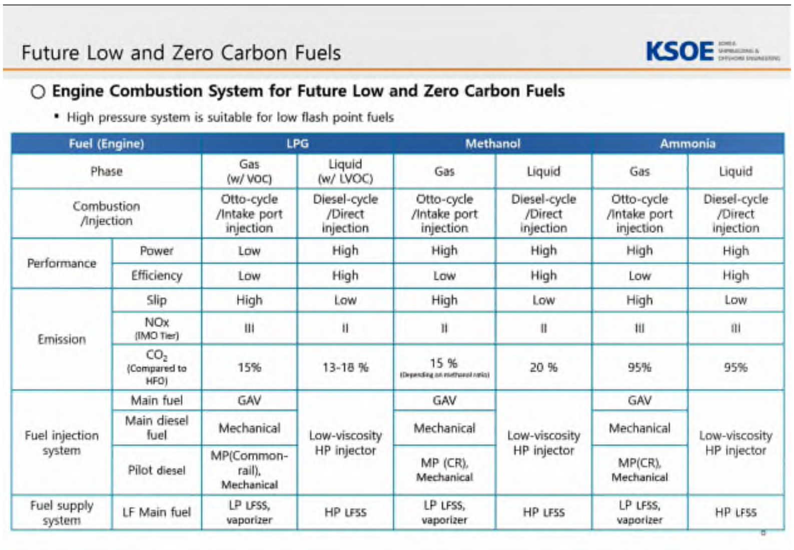
*Figure 12 Pros and cons of advanced marine fuels*



Future Low and Zero Carbon Fuels

KSOE

○ **Engine Combustion System for Future Low and Zero Carbon Fuels**

- High pressure system is suitable for low flash point fuels

| Fuel (Engine) | | LPG | | Methanol | | Ammonia | |
|---|---|---|---|---|---|---|---|
| Phase | | Gas (w/ VOC) | Liquid (w/ LVOC) | Gas | Liquid | Gas | Liquid |
| Combustion /Injection | | Otto-cycle /Intake port injection | Diesel-cycle /Direct injection | Otto-cycle /Intake port injection | Diesel-cycle /Direct injection | Otto-cycle /Intake port injection | Diesel-cycle /Direct injection |
| Performance | Power | Low | High | High | High | High | High |
| | Efficiency | Low | High | Low | High | Low | High |
| Emission | Slip | High | Low | High | Low | High | Low |
| | NOx (IMO Tier) | III | II | II | II | III | III |
| | $CO_2$ (Compared to HFO) | 15% | 13-18 % | 15 % (Depending on methanol ratio) | 20 % | 95% | 95% |
| Fuel injection system | Main fuel | GAV | Low-viscosity HP injector | GAV | Low-viscosity HP injector | GAV | Low-viscosity HP injector |
| | Main diesel fuel | Mechanical | | Mechanical | | Mechanical | |
| | Pilot diesel | MP(Common-rail), Mechanical | | MP (CR), Mechanical | | MP(CR), Mechanical | |
| Fuel supply system | LF Main fuel | LP LFSS, vaporizer | HP LFSS | LP LFSS, vaporizer | HP LFSS | LP LFSS, vaporizer | HP LFSS |

*Figure 13 Engine types for some advanced marine fuels.*

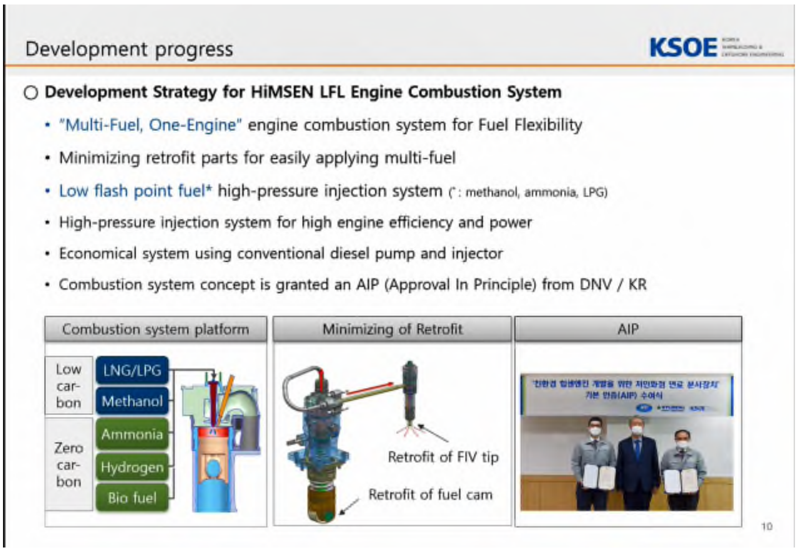



*Figure 14 Development of the HIMSEN multifuel engine*

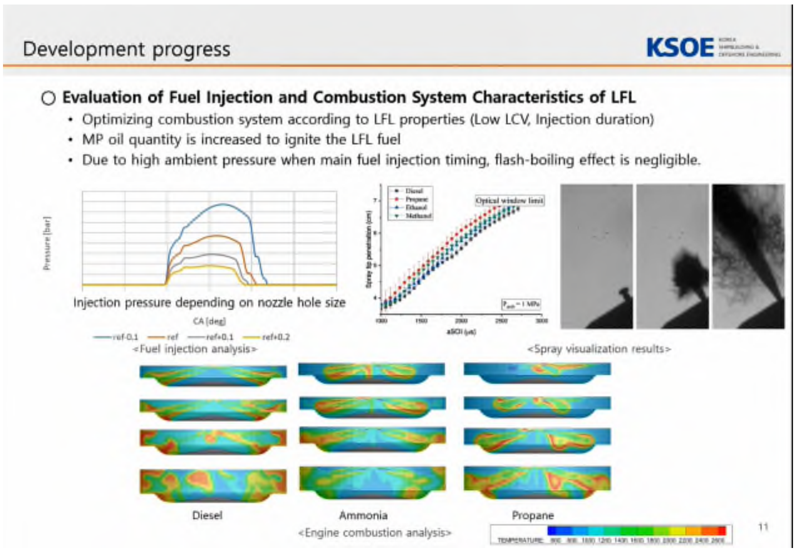



*Figure 15 Injection and ignition processes with some advanced marine fuels*

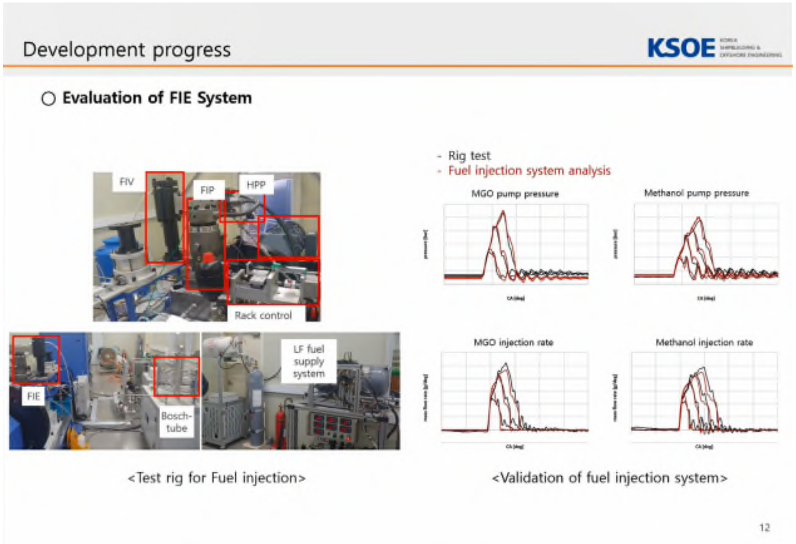



*Figure 16 Fuel injector test rig*

## 4-stroke marine engines

*This section was written by DTI, Denmark.*

4-stroke marine engines are used for propulsion on smaller ships, both with mechanical and diesel electric propulsion systems, for auxiliary power generation, and as emergency power generators. Large 4-stroke DF and SI gas engines are also used worldwide in more than 170 countries for natural gas fired power plants.

Engines range from less than 1 MW and up to around 21 MW in power for a single engine. Table 2 shows data for the smallest and largest medium speed engines offered by MAN ES and Wärtsilä, as examples of large market suppliers. There are several other large suppliers of 4-stroke marine engines for commercial ships such as EMD, ABC, HiMSEN, Niigata, Caterpillar, Cummins etc., many of which are also offering their engines in DF versions for LNG.

*Table 2 Smallest and largest 4-stroke engines available today from MAN ES and Wärtsilä*

| Engine designation | Bore [cm] | Stroke [cm] | Cylinders [number] | Power [MW] | MEP [Bar] | Speed [RPM] |
|---|---|---|---|---|---|---|
| MAN V51/60DF | 51 | 60 | 12 - 16 | 12.6 – 16.8 | 20.6 | 500 |
| MAN L21/31 | 21 | 31 | 6 - 9 | 1.3 – 1.9 | 24.0 | 1000 |
| MAN 175D | 17.5 | 21.5 | 12 - 20 | 1.5 – 4.4 | 18 - 25.5 | 1600 - 2000 |
| Wärtsilä 46TS-DF | 46 | 58 | 6 - 16 | 7.8 – 20.8 | 27 | 600 |
| Wärtsilä 20 | 20 | 28 | 6 - 9 | 1.1 – 1.6 | 21 - 22 | 1000 - 1200 |
| Wärtsilä 14 | 13.5 | 15.7 | 12 - 16 | 0.75 – 1.34 | 22 – 23 | 1500 - 1900 |

### 4-stroke Dual-fuel engines for LNG

The current 4-stroke DF engines have been developed primarily for use with LNG. The gas is injected at low pressure to the inlet ports to form a homogenous mixture, which is ignited by a diesel pilot flame. Combustion occurs by flame propagation, as in SI engines.

DF engines can operate on fuel oil only, which ensures flexibility when LNG is not available or economically unfavorable. The DF engines are in most cases approved as IMO Tier III when operating in gas mode and can be a cost-effective solution to ensure IMO Tier III compliance in ECA zones.

The DF engine can switch instantly from gas to diesel operation. This redundancy prevents sudden loss of power if the LNG system is disabled due to failures or gas leaks in the LNG fuel system.

Some engine types, such as the Wärtsilä 50 DF, are constructed as tri-fuel engines, which can use both low and high viscosity fuels in combination with LNG. The low viscosity distillate fuel types can be used for pilot ignition of the LNG and meet IMO Tier III and sulfur regulation in ECA zones, while the engine can run on LSFO or HFO outside ECA zones.

### 4-stroke LNG monofuel engines

Monofuel gas engines are using the 4-stroke Otto lean burn principle, in which the load is not throttle controlled, but governed by fueling rate and charge air pressure. With a lean fuel/air mixture, these engines can operate with diesel-like compression ratios and efficiency. Rolls-Royce Bergen is a well-known manufacturer of this engine type, which is equipped with prechamber combustion. The gas is ignited within the prechamber, where a spark plug ignites a stoichiometric air/gas mixture. The prechamber combustion produces flames that penetrate and ignite the lean mixture in the cylinder, which is typically very difficult to ignite with spark plugs.

### 4-stroke engines for methanol

Wärtsilä, Himsen and ABC have recently developed dual fuel engines for methanol and are now offering these in their engine programs. The engines from Wärtsilä and Himsen use high-pressure direct injection principles, while ABC uses a low-pressure port fuel injection principle. MAN ES is also developing a methanol DF engine and expects this engine type to be ready for market in 2024.

## Fishing vessels and cargo ships in China

*This section was written by ESC of MVPA of MIIT, China.*

This research report is based on the actual situation and cases that have been carried out in China under the overall framework of the AMF Task 60 of the International Energy Agency Technology Collaboration Program. According to the reserve and future development plan of methanol fuel application technology of Chinese fishing vessels and general cargo ships, after investigation and research within a certain range (excluding all), The actual operation results and the evaluation of its dynamic operation are summarized.

This progress evaluation report is studied and evaluated according to the conventional methods of China's industry, industry and market demand and application, which may be different from the structure given by the topic, but the compiler's principle is to compile based on the principle of no lack of reality and comprehensive description, hoping to inspire and draw lessons from readers.

### Fishing Vessels

In order to protect the sustainable development of marine fishery resources, conserve and rationally utilize marine living resources and control fishing intensity. As early as the beginning of this century, China began to implement the dual control management system for fishing vessels and set control targets for the number of marine fishing vessels and engine power. In 2013, the Chinese government once again issued <Several Opinions on Promoting The Sustainable And Healthy Development of Marine Fisheries (GF [2013] No. 11)>, emphasizing the strict implementation of marine summer fishing moratorium, fishing industry access and aquatic germplasm resources protection, and specifically stating that the pilot of offshore fishing quota should be carried out, the intensity of offshore fishing should be strictly controlled, the control system of marine fishing vessels should be improved, and the number of fishing vessels and the total power of engines should be gradually reduced. It is clear that by 2020, 20000 marine fishing motorboats with a power of 1.5 million kW will be reduced, and the total domestic marine fishing output will be reduced to less than 10million tons. The number of marine fishing vessels in China has been on a downward trend since 2013 and dropped to 147000 in 2019.

Chinese fishing vessels include vessels directly engaged in fishing and aquaculture activities. According to the total power of the main engine, fishing vessels are divided into: 441 kW (including) or more; 44.1 kW (inclusive) -441 kW; There are three categories below 44.1 kW. Divided by ship length: above 24m; 12 (inclusive) -24m; Three types below 12m. Most of China's motorized fishing vessels are less than 12m long. In 2019, China's motorized fishing vessels less than 12m accounted for 78.93% of the total motorized fishing vessels; Motorized fishing vessels with a length of 12-24 meters account for 13.23% of the total motorized fishing vessels, and motorized fishing vessels with a length of more than 24 meters account for only 7.85%, including 220,361 marine fishing vessels and 247951 inland fishing vessels, as shown in Figure 17 and Figure 18.

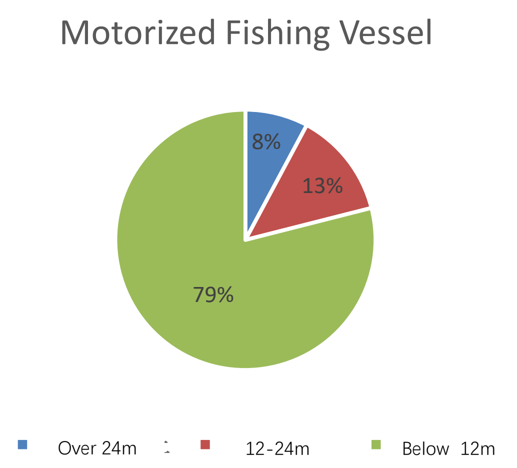



*Figure 17 Length of fishing vessels in China*

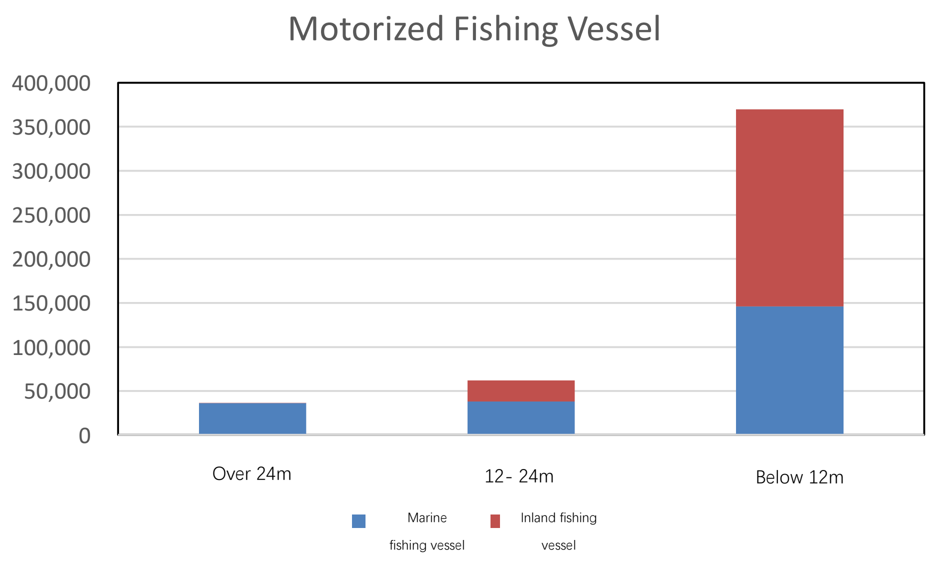



*Figure 18 Number of Chines fishing vessels applicated in marine and inland waterways*

## Inland and Coastal Cargo Ships

By the end of 2020, China had 126,800 water transport ships; The net load was 270.6016 million tons; The passenger capacity was 859,900 seats; The container space was 2.9303 million TEUs.

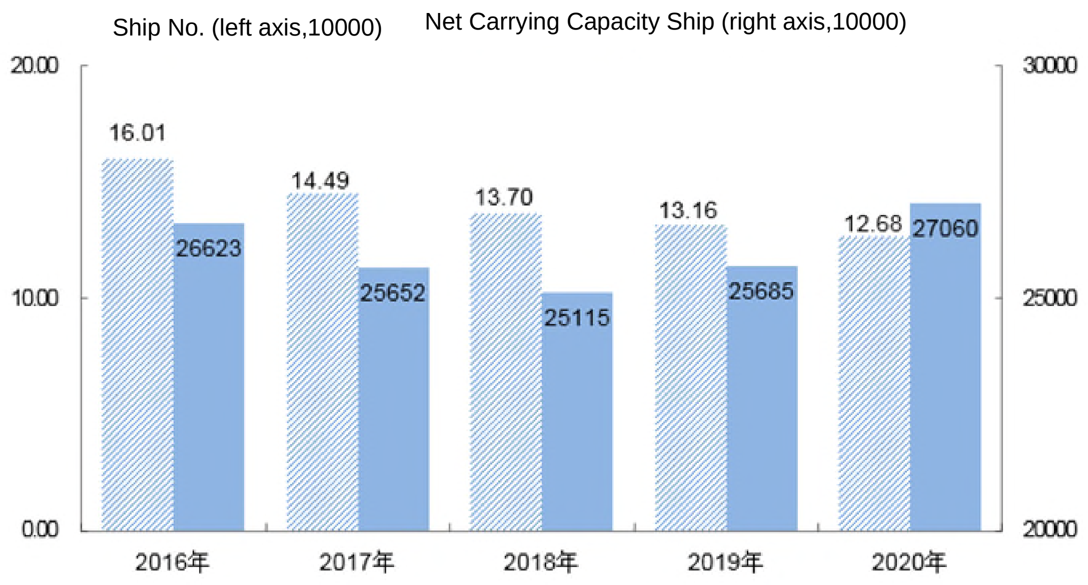



*Figure 19 number of water transport vessels in China from 2016 to 2020*

*Table 3 Composition of national water transport ships (by navigation area)*

| Item | Unit | Data | Increase over the previous year (%) |
|---|---|---|---|
| **Inland waterway transport vessel** | | | |
| No. | 10000 | 11.50 | -3.8 |
| Net Load | 10000/t | 13673.02 | 4.5 |
| Passenger capacity | 10000 | 60.07 | -4.2 |
| Container space | 10000/TEU | 51.31 | 31.0 |
| **Coastal transport vessel** | | | |
| No. | | 10352 | -0.1 |
| Net Load | 10000/t | 7929.83 | 12.0 |
| Passenger capacity | 10000 | 23.63 | 0.6 |
| Container space | 10000/TEU | 60.91 | -3.7 |
| **Ocean shipping vessel** | | | |
| No. | | 1499 | -9.9 |

| | | | |
|---|---|---|---|
| Net Load | 10000/t | 5457.30 | -1.2 |
| Passenger capacity | 10000 | 2.29 | -3.3 |
| Container space | 10000/TEU | 180.80 | 48.9 |

## Coastal Port and Inland Lake Port

### Inland Waterway

By the end of 2020, the navigation mileage of inland waterways nationwide was 127,700 km. The mileage of grade channel was 67,300 km, accounting for 52.7% of the total mileage. The mileage of class III and above channels was 14,400 km, accounting for 11.3% of the total mileage.

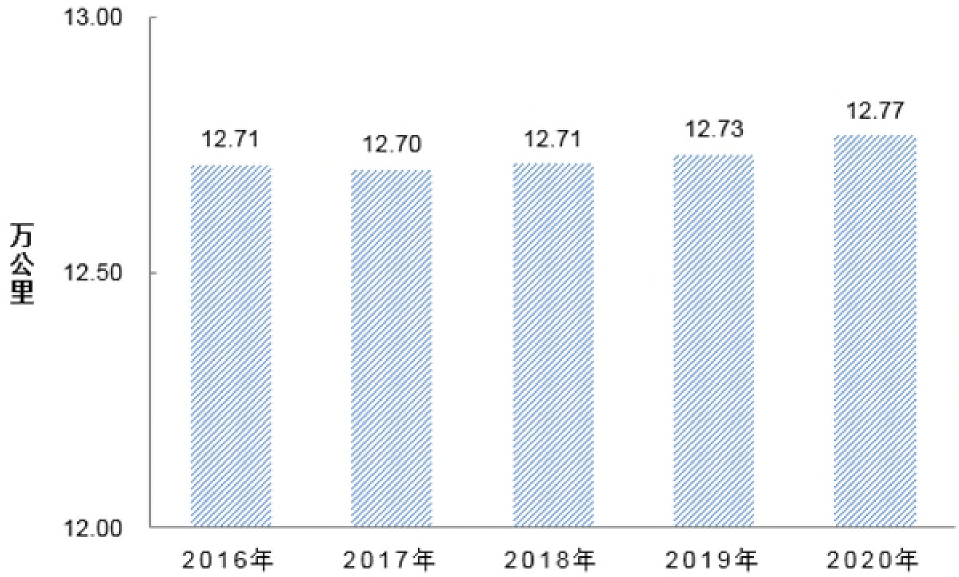



*Figure 20 Navigation mileage of domestic inland waterways from 2016 to 2020*

The navigation mileage of various levels of inland waterways are: 1,840 km of class I waterway, 4,030 km of class II waterway, 8,514 km of class III waterway, 11195 km of class IV waterway, 7,622 km of class V waterway, 17,168 km of class VI waterway and 16,901 km of class VII waterway. The mileage of substandard channels is 60,400 km.

The navigation mileage of inland waterways in each water system is 64,736 kilometers in the Yangtze River system, 16,775 kilometers in the Pearl River (including the Xijiang River Basin), 3,533 kilometers in the Yellow River system, 8,211 kilometers in the Heilongjiang river system, 1,438 kilometers in the Beijing Hangzhou canal, 1,973 kilometers in the Minjiang River System, and 17,472 kilometers in the Huaihe River system.

### Port

In 2020, according to the port data, there were 22,142 wharf berths for production. Among them, 5,461 berths were used for production in coastal ports; There are 16,681 berths for inland port production.

At the end of the year, there were 2,592 berths of 10,000 tons or above in ports nationwide.

Among them, there were 2,138 berths of 10,000 tons or above in coastal ports; There are 454 berths of 10,000 tons or above in inland ports.

*Table 4 number of berths of 10000 tons and above in ports in China*

| Berth tonnage | National ports | Increase | Coastal port | Increase | Inland Port | Increase |
|---|---|---|---|---|---|---|
| Total | 2592 | 72 | 2138 | 62 | 454 | 10 |
| 1-3/10000t | 865 | 6 | 672 | 2 | 193 | 4 |
| 3-5/10000t | 437 | 16 | 313 | 16 | 124 | 0 |
| 5-10/10000t | 850 | 28 | 725 | 22 | 125 | 6 |
| ＞100000t | 440 | 22 | 428 | 22 | 12 | 0 |

At the end of the year, there were 1371 specialized berths among the 10000 ton berths and above in China; 592 general bulk cargo berths; 415 general cargo berths.

*Table 5 composition of berths of 10000 DWT and above in China (by main purposes)*

| Berth Use | 2020 | 2019 | Increase |
|---|---|---|---|
| Specialized berth | 1371 | 1332 | 39 |
| Container berth | 354 | 352 | 2 |
| Coal berth | 265 | 256 | 9 |
| Metal ore berth | 85 | 84 | 1 |
| Crude oil berth | 87 | 85 | 2 |
| Product oil berth | 147 | 143 | 4 |
| Liquid chemical berth | 239 | 226 | 13 |
| Bulk grain berth | 39 | 39 | 0 |
| General bulk cargo berth | 592 | 559 | 33 |
| General cargo berth | 415 | 403 | 12 |

## Traffic Capacity, Comprehensive Passenger And Freight Capacity

In 2020, statistics showed that China completed 47.36 billion tons of commercial freight. Among them, 4.46 billion tons of railway freight, accounting for 9.4%; Highway freight transport reached 34.26 billion tons, accounting for 72.3%; Waterway freight transport reached 7.62 billion tons, accounting for 16.1%. The annual turnover of goods reached 19676.09 billion ton kilometers. Among them, the railway freight turnover is 3051.45 billion ton kilometers, accounting for 15.0%; The highway freight turnover is 6017.18 billion ton kilometers, accounting for 29.8%; The turnover of waterway cargo is 10583.44 billion ton kilometers, accounting for 52.4%.

### Chemical Transport Capacity of Coastal Shipping

Statistics show that by the end of 2019, China's coastal chemical transport ships (including methanol, oil products, chemicals and other goods) had a total of more than 280 ships and more than 1.12 million deadweight tons. The annual transportation volume of chemical ships has reached 32 million tons, and methanol is one of the main cargo types for the transportation of bulk chemicals.

### Chemical Transport Capacity of Inland Waterway Shipping

At present, China's Yangtze River system has about 3000 vessels transporting dangerous goods, including more than 1100 chemical vessels. The annual transportation volume was about 88million tons, including 31million tons of chemicals.

### Marine Fuel standard for China

At present, China has implemented a mandatory national standard for marine fuel oil, <GB17411-2015 marine fuel oil>, which is applicable to fuel oil for marine diesel engines and their boilers.

After the implementation of the law of <The People's Republic of China on The Prevention And Control of Air Pollution> in 2016, the fuel oil for ships in inland river areas is specified as ordinary diesel oil.

The fuel meeting the requirements of GB17411 is applicable to marine diesel engines and their boilers, including distillate type and residue type：

Distillate type: suitable for medium and high speed marine diesel engines;

Residue type: suitable for medium and low speed high-power marine diesel engines.

The promotion of methanol vehicles and the use of methanol fuel in China has started the work of methanol fuel standards. At present, the two national standards <M100 methanol fuel for vehicles >and <alcohol based liquid fuel >have entered the stage of review, release and revision respectively. Methanol fuel for ship power is proposed to be implemented in accordance with M100 methanol fuel for vehicles. After a certain market guarantee scale is formed, the industry standard for "methanol fuel for ship power" will be prepared.

## Emission Regulations in China

*Table 6 IMO emission limits at each stage*

| Tier | Date | Emission Limit, g/kWh | | |
|---|---|---|---|---|
| | | n<130 | 130≤n<2000 | n≥2000 |
| Tier I | 2000 | 17.0 | 45·n^-0.2 | 9.8 |
| Tier II | 2011 | 14.4 | 44·n^-0.23 | 7.7 |
| Tier III | 2016 | 3.4 | 9·n^-0.2 | 1.96 |

*Table 7 First stage emission limits of marine engine exhaust pollutants*

| Type | Single cylinder displacement (SV) (L/C) | Rated net power (P)(kW) | CO (g/kWh) | HC+ $NO_X$ (g/kWh) | CH4(1) (g/kWh) | PM (g/kWh) |
|---|---|---|---|---|---|---|
| I | SV＜0.9 | P≥37 | 5.0 | 7.5 | 1.5 | 0.40 |
| | 0.9≤SV＜1.2 | | 5.0 | 7.2 | 1.5 | 0.30 |
| | 1.2≤SV＜5 | | 5.0 | 7.2 | 1.5 | 0.20 |
| II | 5≤SV＜15 | | 5.0 | 7.8 | 1.5 | 0.27 |
| | 15≤SV＜20 | P＜3300 | 5.0 | 8.7 | 1.6 | 0.50 |
| | | P≥3300 | 5.0 | 9.8 | 1.8 | 0.50 |
| | 20≤SV＜25 | | 5.0 | 9.8 | 1.8 | 0.50 |
| | 25≤SV＜30 | | 5.0 | 11.0 | 2.0 | 0.50 |

(1) Only applicable to NG (including dual fuel) marine engine。

*Table 8 First stage emission limits of marine engine exhaust pollutants*

| Type | Single cylinder displacement (SV) (L/C) | Rated net power (P)(kW) | CO (g/kWh) | HC+ NOX (g/kWh) | CH4(1) (g/kWh) | PM (g/kWh) |
|---|---|---|---|---|---|---|

| | | | | | | |
|---|---|---|---|---|---|---|
| Ⅰ | SV＜0.9 | P≥37 | 5.0 | 5.8 | 1.0 | 0.3 |
| | 0.9≤SV＜1.2 | | 5.0 | 5.8 | 1.0 | 0.14 |
| | 1.2≤SV＜5 | | 5.0 | 5.8 | 1.0 | 0.12 |
| Ⅱ | 5≤SV＜15 | P＜2000 | 5.0 | 6.2 | 1.2 | 0.14 |
| | | 2000≤P＜3700 | 5.0 | 7.8 | 1.5 | 0.14 |
| | | P≥3700 | 5.0 | 7.8 | 1.5 | 0.27 |
| | 15≤SV＜20 | P＜2000 | 5.0 | 7.0 | 1.5 | 0.34 |
| | | 2000≤P＜3300 | 5.0 | 8.7 | 1.6 | 0.50 |
| | | P≥3300 | 5.0 | 9.8 | 1.8 | 0.50 |
| | 20≤SV＜25 | P＜2000 | 5.0 | 9.8 | 1.8 | 0.27 |
| | | P≥2000 | 5.0 | 9.8 | 1.8 | 0.50 |
| | 25≤SV＜30 | P＜2000 | 5.0 | 11.0 | 2.0 | 0.27 |
| | | P≥2000 | 5.0 | 11.0 | 2.0 | 0.50 |
| (1) Only applicable to NG (including dual fuel) marine engine. | | | | | | |

According to the medium and long-term development plan put forward by China, based on the development goal of 2035, build and realize the " carbon neutralization and carbon peak" development goal, ensure the market demand, and have an intelligent and modern inland and coastal shipping system. Improve the capacity of inland shipping infrastructure, transportation services, green development, safety supervision, etc., and improve the navigation capacity of 1000 ton inland waterway. The promotion and application of low-carbon clean energy and renewable methanol energy as well as the guaranteed capacity for filling have been significantly improved.

## Regulation of $SO_X$ and $NO_X$ from ships

*This section was written by DTI, Denmark.*

This section focuses on the impact of the $NO_X$ and $SO_X$ regulations on existing and new ships worldwide, as well as the status for use of new alternative fuels which in many cases are used in compliance solutions.

The marine sector has historically operated with very limited regulation of their exhaust emissions. Emissions of $NO_X$ and $SO_2$ (and indirectly also particulate matter) have however been subject to regulation from around the year 2000, as growing concern has been raised on health and environmental effects caused by these emissions.

With increasing focus on and ambitious targets for the $CO_2$ emissions in the marine sector, new fuel alternatives with lower carbon footprints are now being considered. These new fuels, however, require new engine technologies, which are still in the early stages of development and demonstration.

Detailed statistics for scrubber installations and alternative fuels used in this report are provided by DNV Veracity Alternative Fuel Insight database. The statistics provide an insight into the preference for and state of implementation for this technology as a means for reaching sulfur compliance, compared to continued operation with compliant fuel sulfur.

### Environmental and health effects of sulfur and nitrogen dioxide

Exposure to sulfur dioxide ($SO_2$) is known to trigger respiratory and pulmonary illness in humans. It also forms sulfurous acid ($H_2SO_4$) which contributes to soil acidification, and furthermore participates in the formation of secondary particulate matter, which also affects human health.

Nitrogen Oxides ($NO_X$) consist of NO and $NO_2$. While NO is not considered harmful, it reacts with ozone in the atmosphere to form $NO_2$, which is toxic to humans. As with $SO_2$, it contributes to acidification by formation of nitric acid ($HNO_3$). It also contributes to the formation of smog and secondary particulate matter.

### Historical development in marine emission regulation

From year 2000 to 2012, marine engines were allowed to operate with heavy fuel oil containing up to 4.5 % (by weight) sulfur. In the same period, EU land-based transportation and non-road machinery diesel sulfur limits were reduced from 350 ppm (year 2000) to 10 ppm (year 2009). This reduction was at first motivated by insight in the negative effects of sulfur dioxide on human health and the environmental impact, later by the introduction of diesel exhaust after-treatment systems for PM and $NO_X$, with catalytic coatings that are intolerant to sulfur.

Desulfurization and $NO_X$ reduction was developed for power plants and waste incineration plants from around 1980, and these technologies are today effective in reducing $SO_2$ and $NO_X$ emissions on most modern power plants in the EU. While $SO_2$ and $NO_X$ emissions from land-based transportation and power plants were reduced significantly with these new technologies, an increase in marine traffic soon caused the marine sector to become one of the dominant sources of airborne $SO_2$ and $NO_2$ in the EU region. This moved focus from land-based sources to exhaust emissions from ships, and even more focus on sensitive regions such as the Baltic region and the coastlines in North America.

## ECA zones

The zones depicted in Figure 21 show the current Emission Control Areas, as well as those under discussion. In these areas, emissions of $SO_2$ and $NO_X$ are subject to lower limits than global waters. The limits have been implemented in separate regulatory processes, which are presented in the following chapters.

The ECA zones regulating the $NO_X$ emissions are geographically identical to those regulating $SO_X$ emissions. $NO_X$ emissions are however regulated through the IMO Tier III regulation, which is only relevant for ships that are built after the date of enforcement.

The fuel sulfur regulation applies to all ships, disregarding date of build. It is intended to limit emissions of $SO_2$ from ships, through either use of low sulfur fuels oil, $SO_X$ scrubbers or alternative sulfur-free fuels. Dates of enforcement are valid for both the North American ECA and North/Baltic Sea ECA.

The IMO Tier regulation for $NO_X$ applies to new ships, which are keel laid after the date of enforcement. These new ships must comply with IMO Tier III when operating inside the ECA zones.

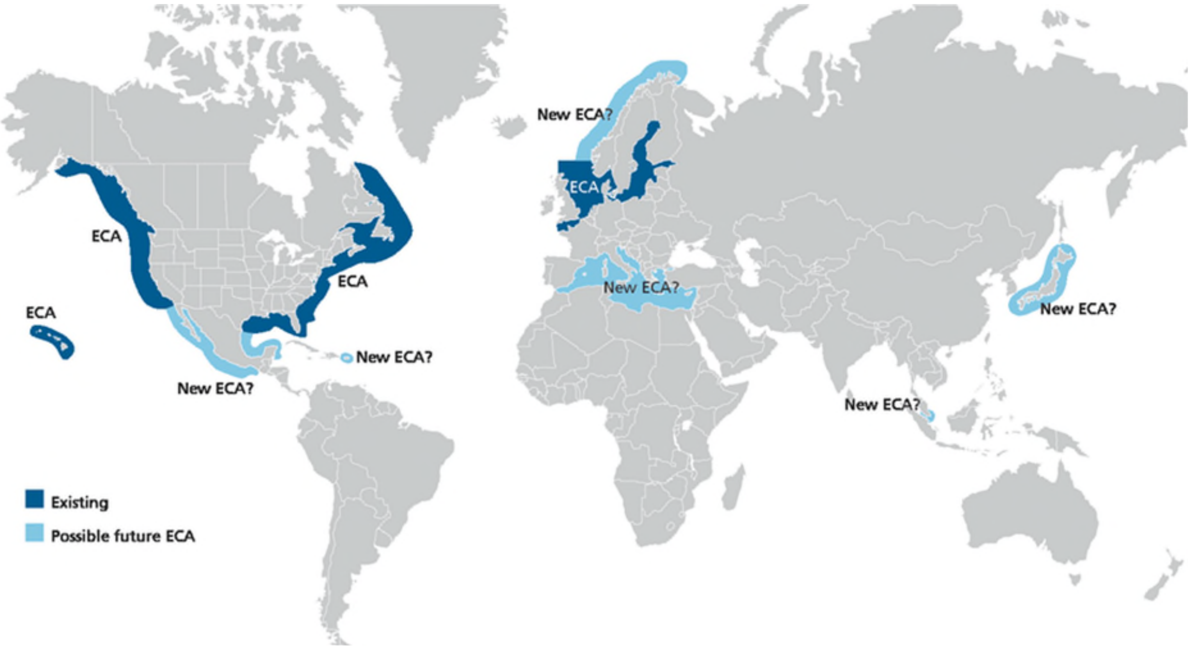



*Figure 21: Current and possible future ECA zones. Illustration by DNV GL*

At the latest MEPC meeting (MEPC 78) it was officially proposed to assign the Mediterranean Sea as a new $SO_X$ ECA zone. The proposal will now be considered by the IMO member countries, and if accepted at the upcoming MEPC 79, the new $SO_X$ ECA zone can be effective from 2025.

## Sulfur regulation

Starting from 2005, emission Control Areas (ECAs) were established along the North American and Caribbean Sea coastlines, in the Baltic Sea and part of the North Sea. Since 2015, emissions of sulfur dioxide must correspond to fuel with 0.1 % sulfur or less within these zones. From 2020, ships operating globally (outside the zones) must now also operate with fuel oil containing no more than 0.5 % sulfur.

The limit for fuel sulfur content in the $SO_X$ ECA zones and globally has been regulated by MARPOL 73/78 Annex 6, beginning from year 2000.

All ships are required to comply with the fuel sulfur regulation, either by using compliant fuel or by removing the sulfur dioxide from the exhaust to a level equal to or less than that resulting from use of compliant fuel.

The latest regulation steps are:

- In 2015, the ECA limit was lowered from 1.0 % fuel sulfur to 0.1 % fuel sulfur in ECA zones. Fuel meeting this specification can be distillate fuel quality, but as such no requirements are made to the fuel other than the sulfur content.
- In 2020, the global limit was lowered from 3.5 % to 0.5 %. This limit was enforced after a long process in making sure that the demand for this fuel specification could be met. In general, fuel of this quality is heavy fuel oil which has been desulfurized, and often mixed with higher fuel qualities to further lower the sulfur content to the limit.

The development in the allowable fuel sulfur content in global waters and in the designated ECA zones is illustrated in Figure 22.

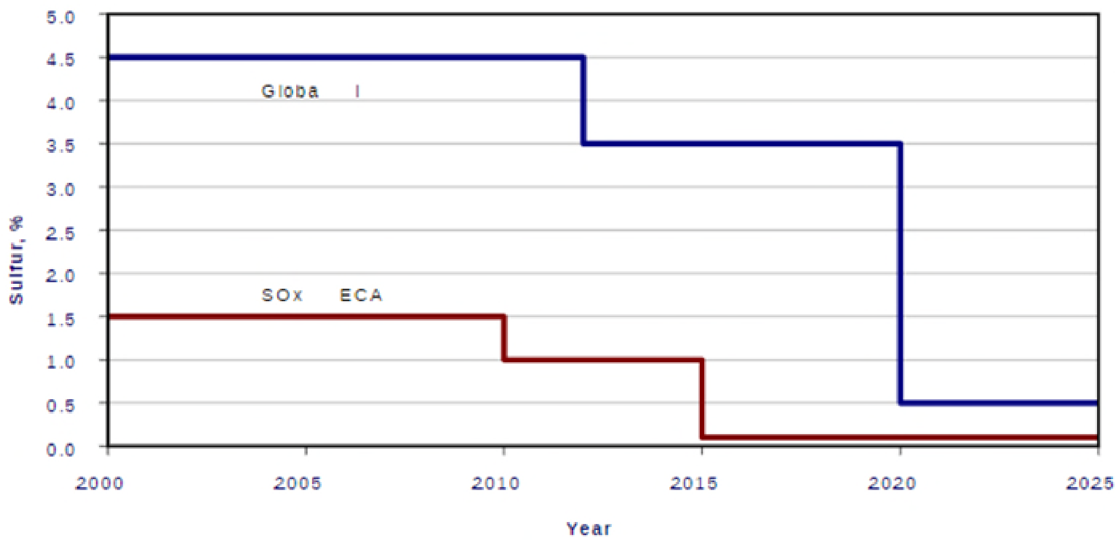



*Figure 22: Sulfur limit in global waters and ECA zones. Illustration from Dieselnet.com*

### Fuel switch-over

The difference in fuel sulfur limits between global waters and ECA zones means that many ships operating in both ECA zones and global waters will carry fuels with both 0.5 % and 0.1 % sulfur. When a ship enters or leaves the ECA zone, the fuel type can be switched to be complaint in the ECA zone. This is a standard procedure on ships operating on more than one type of fuel oil. The switchover must be completed in due time to ensure that residual fuel with high sulfur content is consumed before entering the $SO_X$ ECA.

### Carriage ban

To make it more difficult for ships not retrofitted with scrubbers in continuing with operation on fuel oil with high fuel sulfur content, IMO has made an amendment to regulation Annex 6, which implements a carriage ban for non-compliant fuels on ships without scrubbers. The carriage ban entered into force on 1.st of March 2020 (IMO, 2020), two months after the new regulation limiting the fuel sulfur content to 0.5 %.

The carriage ban mainly supports the authorities in enforcing the fuel sulfur regulation, which is done by routine inspections to extract fuel oil samples, which are analyzed for fuel sulfur content. These inspections are often performed on suspected cases, where drone inspections with chemical sensors or other remote sensing technologies have indicated higher than normal levels of sulfur dioxide in the exhaust plume of a given ship.

A similar carriage ban for HFO in arctic zones will be enforced from 2024, to reduce the black carbon pollution in these sensitive regions. Black carbon emitted from ships is believed to be a major contributor to the reduction of the light reflection (albedo effect) on permanent ice covers, which accelerates the melting of these ice covers as the ice absorbs more heat from the sun rather than reflecting it.

## $NO_X$ regulation

$NO_X$ is regulated through the MARPOL 1973/1978 convention Annex VI: Prevention of Air Pollution from Ships.

The regulation has been made in three steps, known as Tiers, implemented from the beginning of 2000. Tier I applies to ships built from the year 2000 to 2011. From 2008, the regulation was furthermore applied to engines on ships built between 1990 and 2000, with more than 90 L of displacement per cylinder and more than 5 MW output, subject to availability of approved engine upgrade kits. Tier II applies to new ships built from 2011, operating in global waters. This emission limit could be reached with improved engine technology and combustion optimization. Tier III applies to new ships operating within the designated ECA zones, with implementation dates as described below.

- For the ECA zones in North America and US Caribbean Sea, IMO Tier III entered into force on January 1.st, 2016, for ships keel laid after this date.
- For the ECA zones in the Baltic Sea and the North Sea, IMO Tier III entered into force on January 1.st, 2021, for ships keel laid after this date.

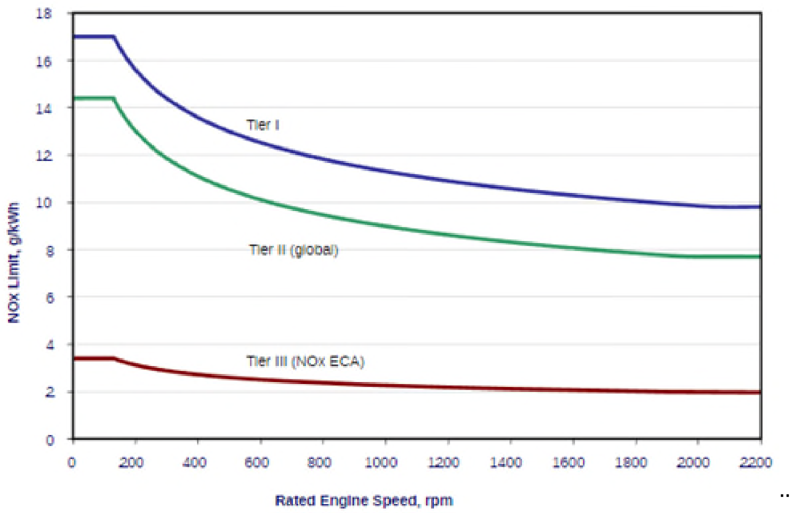



*Figure 23: NOx emission limit for Tier I, II and III. Illustration from Dieselnet.com*

## The North American $NO_X$ ECA

IMO Tier III regulations were first enforced for new ships operating in the North American ECA from 2016. Although it was expected that this would lead to a growing number of ships with SCR, the reality was that new ships would be built to operate in other parts of the world, where the global $NO_X$ regulations (Tier II) were sufficient. The US ECA region was instead served with existing ships, while new ships would be used for other regions to avoid the Tier

III compliance requirement in the US ECA. This challenged the ambition of $NO_X$ reduction.

### The North Sea and Baltic Sea $NO_X$ ECA

The North Sea and Baltic ECA zones for IMO Tier III compliance entered into force from January 2021, five years after the North American ECA. The $NO_X$ ECA zones were originally intended to be enforced simultaneously in both the North American and Baltic/North Sea, but the latter was postponed five years as a direct consequence of a protest from the Russian Federation, which was supported by 6 other EU countries (Transport & Environment, 2016). The main arguments against were that the technology was not sufficiently developed or available.

## Impact of the $NO_X$ and $SO_X$ regulations

*This section was written by DTI, Denmark.*

The regulation of emissions from marine engines has resulted in the development of specific technologies that enable compliance of the existing engine technologies with advanced aftertreatment systems for reduction of $SO_2$ and $NO_X$.

The regulations have also acted as a motivation for an increased use of LNG as an alternative fuel. In many cases, LNG can be used in solutions that comply with both the sulfur and $NO_X$ regulations.

With increasing focus on $CO_2$ emissions, marine engines are now also being developed for future fuels such as methanol and ammonia, which has the potential of reducing emissions of particulate matter and black carbon as well.

### Impact of the $NO_X$ regulation

The most notable impact from the regulation of $NO_X$ has been the development and implementation of EGR and SCR solutions for exhaust after-treatment. These technical solutions can reduce the $NO_X$ in the exhaust gas from 2-stroke engines with approx. 80 % compared to Tier II levels. While 4-stroke engines can generally only be Tier III compliant with SCR, or in DF operation with LNG as fuel, 2-stroke engines can be constructed to comply with the Tier III regulation with several technical solutions and alternative fuels.

#### Statistics for Tier III compliant 2-stroke engines

MAN ES, which has a leading market position for 2-stroke engine sales, has provided statistics from their reference list for 2-stroke engine deliveries, which include detailed information on the Tier level, fuel technology, and emission control technology. Data from this reference list is used to illustrate the development in Tier III engine deliveries and the technologies used for these engines, as well as deliveries of new engines for LNG.

Figure 24 displays the development in Tier III engines delivered from 2015, including ordered engines to be delivered. Most Tier III compliant engines delivered from MAN ES are equipped with high-pressure SCR (HPSCR), which indicate that these engines are intended or prepared to operate with fuel oil containing more than 0.1 % sulfur. The second most common solution is EGR (all variants), which is not sensitive to fuel sulfur content. The low share of low-pressure SCR (LPSCR) indicates that only a small share of the engines delivered are intended solely for ULSFO (0.1 % sulfur) or LNG.

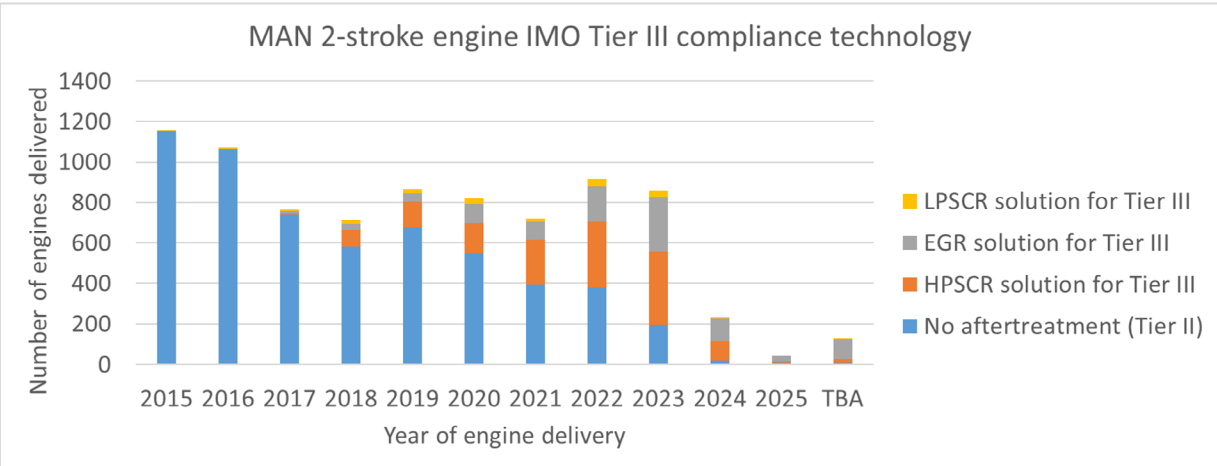



*Figure 24: Technology choice for IMO Tier III compliance*

Figure 25 show the share of Tier III engines delivered for alternative fuels compared to fuel oil, from 2015 and including ordered engines. The figure shows that the market share for DF gas engines has grown very rapidly in 2022, and that methanol engines have become visible in the sales statistics. A total of 24 DF engines for methanol have been delivered to and including 2022, and 44 additional methanol DF engines are to be delivered.

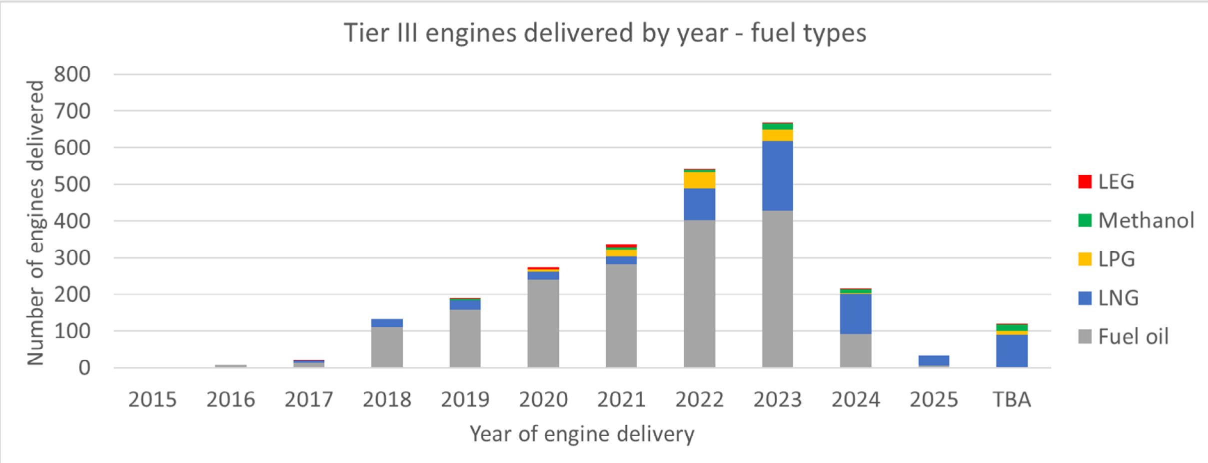



*Figure 25: 2-stroke Tier III engine fuel design deliveries by year*

## Tier II and Tier III mode operation

Ships are in most cases designed and intended to operate both in and outside ECA zones. Due to extra costs associated with operating in Tier III mode, most engines designed to switch between Tier II and Tier III operating modes, with use of after-treatment technology, specific engine settings, and alternative fuels which act together to reduce $NO_X$ formation to reach the emission compliance level. Tier III operating modes are enabled when entering ECA zones, in which the $NO_X$ limit is approx. 5 times lower than in global waters.

The crew of the ship ensure that the ship is compliant when entering an ECA zone by shifting the operating mode of the engines, which engages SCR/EGR and a specific engine tuning that lowers $NO_X$ in combination with the aftertreatment system. With dual fuel engines, the engine must be operating in Tier III mode with LNG or any other fuel which makes it compliant with Tier III.

Only ships which are built for lifetime operation outside the ECA zones are constructed without Tier III engines. These constitute a minor part of all ships, as reflected by the statistics for 2-stroke engines Tier III compliance in Figure 24.

## Local regulations

The increasing awareness of the environmental and human effects of $NO_X$ has resulted in national policies and incentives independent of the IMO regulation.

An example of such a policy is the Norwegian $NO_X$ fund, which collects $NO_X$ taxes for ships operating in the national waters of Norway and use this to fund initiatives that reduce $NO_X$. This has resulted in subsidies for construction of many LNG ships, as well as SCR installations. LNG is strongly supported in Norway due to the availability of LNG from the large refining facilities on the Norwegian coast, along with a well-established infrastructure and bunkering facilities for LNG.

Other countries seek to reward ships which are Tier III compliant through differentiating harbor taxes. As an example, Sweden has introduced this for some of their large harbors. Ships that can document their $NO_X$ emission reductions are given a reduction in harbor taxes.

## Impact of sulfur regulation

As consequence of the sulfur regulation, ship owners have been forced to choose between using compliant fuel oil or installing Exhaust Gas Cleaning Systems (ECGS, commonly named scrubbers). Since around 2012 (Flex LNG Ltd., 2021), a third option when ordering new ships has been to use LNG as fuel, which automatically meets the regulation demand.

Compliant fuel oils are commonly named “very low sulfur fuel oil” (VLSFO), which may contain up to 0.5 % sulfur, and “ultra-low sulfur fuel oil (ULSFO), which may contain up to 0.1 % sulfur. Alternative fuels such as LNG, LEG, LPG and methanol are always compliant, as they do not contain any fuel sulfur.

The alternative to use of compliant fuel oils is to use $SO_2$ scrubbers to remove the sulfur from the exhaust gas. The latest tightening of the sulfur cap to 0.5 % in 2020 has forced many ship owners with fleets in deep sea shipping operation to consider the choice between scrubber solutions and the more expensive VLSFO. Switching to VLSFO increases the fuel costs and makes the operator fully dependent on the availability of VLSFO. Scrubbers on the other hand allow the ships to continue operation with HFO, but the investment in scrubber installations is considerable, including lost revenue from transportation, and the risk of losing market shares.

### Fuel oil consumption change from 2019 to 2020

The regulation has resulted in a large increase in demand for light fuel oils, which is reflected in consumption data gathered by IMO. IMO enforced the collection of fuel consumption data by the MEPC.278(70) resolution, and reports for 2019, 2020 and 2021 are available on the IMO website (https://www.imo.org/en/OurWork/Environment/Pages/Data-Collection-System.aspx). The MEPC report on fuel oil consumption in 2020 accounts for approx. 27.000 ships and 94 % of all ship gross tonnage, for ships above 5000 GT.

The fuel sulfur regulation has resulted in a large increase in demand for light fuel oils, and the oil refineries have succeeded in meeting this demand timely. In general, refinery capacity, fuel availability and bunkering facilities have been adequately expanded to satisfy the demand for light fuel oils, such that all ships which were not equipped with scrubbers at the transition were able to change to these fuels.

Figure 26 illustrates the change in fuel consumption data from 2019 to 2020, which reflects the fuel consumption before and after the date of enforcement for use of LSFO (0.5 %) in global waters. It is clear that a very large amount of HFO has been substituted with light fuel oil in 2020, although HFO still accounted for close to 50 % of all fuel oil consumption in 2020.

The data collected is however intended solely for calculation of the carbon intensity calculation (CII) for ships and does not provide any information about the fuel sulfur content. It is therefore not possible to estimate the share of fuel oil consumed which was compliant with fuel sulfur regulation, and which share required the use of scrubbers in global waters or ECA zones. The data does, however, indicate that a very large share of the fuel being sold and consumed by ships is now being refined, which is a process that normally also implies that fuel sulfur is being reduced.

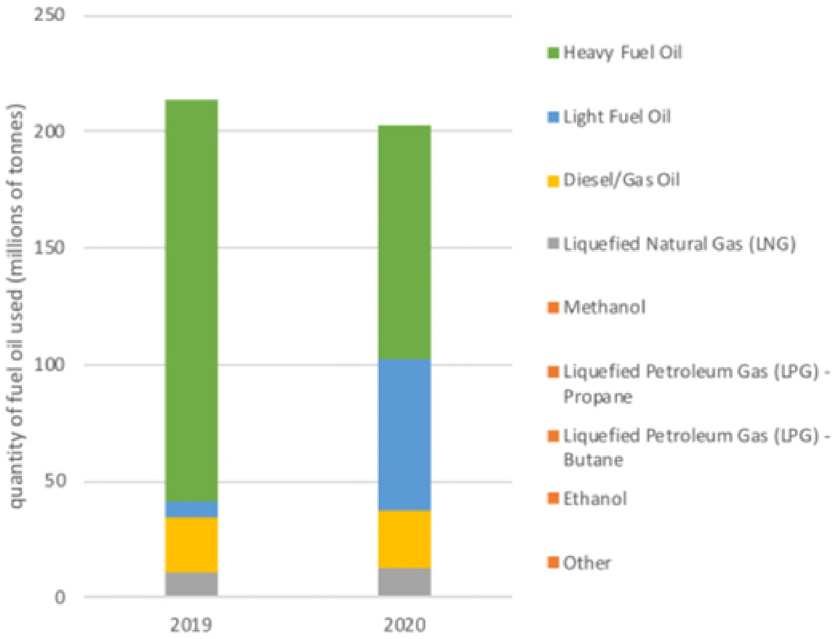



*Figure 26: Fuel oil consumption reported for ships above 5000GT in 2019 and 2020. Figure from IMO document MEPC 77/6/1 - Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2020)*

## Increased use of LNG as marine fuel

The emission regulations have caused a widespread adaptation and acceptance of LNG as marine fuel. Although considerably more complicated in handling and storage, LNG does not contain sulfur, which eliminates the need for scrubbers. In some applications, using LNG can also be an economical solution to make ships IMO Tier III compliant.

The introduction of LNG has required a large amount of technical and regulatory developments but has been an important step away from a very conservative position in the marine sector, which for decades has been relying on cheap, but also heavily polluting fuel oil.

4-stroke DF engines with LNG as primary fuel were introduced around 2002 and initially used only on LNG carriers. These engines were IMO Tier II and sulfur compliant without aftertreatment, which allowed them to operate without SCR and $SO_X$ scrubbers. From 2013, 4-stroke DF engines have also been IMO Tier III compliant.

2-stroke DF engines for LNG became available around 2012. The low-pressure variants of these 2-stroke engines are IMO Tier III compliant with only EGR aftertreatment, whereas their high-pressure counterparts require either SCR or EGR for $NO_X$ compliance in the ECA regions.

Today, LNG is a feasible alternative to fuel oil. Almost a third of ships on order in 2023 are being prepared for LNG as primary fuel. With increasing focus on the global warming and $CO_2$ reductions, it is however now considered to be a temporary solution for ships, while production and infrastructure is prepared for fuels that provide a lower carbon footprint, such as synthetic fuels produced with renewable energy, biofuels and even zero carbon fuels such as hydrogen and ammonia. The technology that enables the use of these new fuels is not yet in place but will likely be ready within this decade. The current uncertainty is mostly which fuels will be dominating the market.

# Impact of particulate matter, soot, and Black Carbon regulation

*This section was written by DTI, Denmark.*

Sources of particulate emissions from land-based activities are generally well regulated today. Most modern power plants in developed countries are required to prevent emissions of soot. In the EU passenger vehicles have been equipped with highly efficient particle filters from Euro 4, and heavy-duty vehicles since Euro VI. Before that, the reduction in fuel sulfur and the development in engine technology has ensured compliance with the less strict emission limits for soot, that preceded today's standards. Most other developed nations worldwide have introduced similar demands to limit pollution with particulate matter.

## Regulation of particulate matter

### EU stage regulation for Inland Waterways

Ships operating on rivers and lakes (Inland Waterways) in the EU has been included in the EU Non-Road Stage regulation (Dieselnet, 2023) since Stage III, which entered into force in 2007. Engines in Stage III were however generally compliant with the PM limit without particle filters. Stage V, which has entered into force for engines produced after 2020, introduced a limit on particle concentration (PN) for engines above 300 kW, which necessitates the use of diesel particulate filters. From October 2022, engines above 300 kW installed in new vessels must be Stage V.

### US EPA regulation

The US EPA regulation treats engines in marine vessels with a displacement volume of less than 7 liters per cylinder as non-road engines (category 1), and engines with less than 30 liters per cylinder as locomotive engines (category 2). Above that, engines are considered unique marine designs, which are not covered by EPA regulation, but are expected to comply with the IMO regulation.

The latest EPA regulation is Tier 4, in which the PM limit is 0.04 g/kWh for engines between 600 and 3700 kW, and 0.06 g/kWh for category 1 and 2 engines above 3700 kW. This limit is comparable to the EU Stage IIIB (0.025 g/kWh), which at that time in many cases forced the use of particulate filters on many new machines. It is however possible to make modern marine engines compliant with this PM limit without DPF, provided that the engines use transport diesel without sulfur as fuel.

The EPA regulation is a domestic regulation that applies to engines installed on US ships only. Ships visiting the US are only expected to comply with IMO regulations.

### IMO regulation

For ships on open sea, emission of particulate matter, commonly known as soot particles, is only indirectly regulated through the regulation of fuel sulfur in MARPOL protocol, Annex VI. Since fuel sulfur contributes to particulate formation, regulating the allowed fuel sulfur content has a direct effect on the amount of soot that is emitted from the ships.

The lack of regulation can be attributed to a lesser focus on marine emissions, as well as a lack of technical solutions to effectively prevent particulate emissions from ships. As the focus on particulate emissions is increasing, solutions to handle this type of emissions are also becoming more relevant.

The use of particulate filters on marine engines in general is however largely prevented by a range of technical challenges, which are related to specific engine technology and the composition of the exhaust. These challenges are addressed later in this report.

## Energy Efficiency and Greenhouse Gas regulation

The Energy Efficiency Design Index (EEDI) is an IMO regulation that entered into force for new ships from 2015. It provides a measure for the $CO_2$ emissions relative to the transport work, measured as the ratio of $CO_2$ emitted to the product of tons of cargo and distance in nautical miles. New ships will be required to have lower EEDI ratings, as the limit is reduced from in 2025.

Ships fueled with LNG emit less $CO_2$, as methane has a higher hydrogen-to-carbon ration than fuel oil. The conversion factor (Cf, tons of $CO_2$ per ton of fuel) for methane is 2.75, and 3.1-3.2 for fuel oils. This lower value will in some cases be sufficient to reduce the EEDI below the required limit for certain ship types. Future reductions in the required EEDI for new ships will likely increase the use of LNG, as well as other fuel options such as methanol.

Ships designed with dual fuel engines must be able to store at least 50 % of the onboard fuel energy as LNG, if LNG is to be regarded as primary fuel. In that case, the lower conversion factor can be used in the EEDI calculation, otherwise it will be calculated as a weighted average of LNG and fuel oil capacities. This rule is intended to limit operation with fuel oil on ships that are originally designed for LNG propulsion, mainly by reducing the operational range of ships which choose not to use LNG in operation.

The EEDI does however not consider the high GWP of methane. With 2-stroke engines that have direct high-pressure injection, methane emissions are very low. With 4-stroke DF engines, the slip can be more than 1% of the fuel supplied and this will often result in higher $CO_2$ equivalent emissions, which effectively reduces the potential $CO_2$ reductions with natural gas as fuel.

### FuelEU Maritime regulation

This new regulation will oblige ships above 5,000 gross tonnes calling European ports, except for fishing ships, to reduce the greenhouse gas intensity of the energy used on board starting in 2025. This is expected to have major impact on the marine traffic within EU and to/from EU (Counsil, 2023).

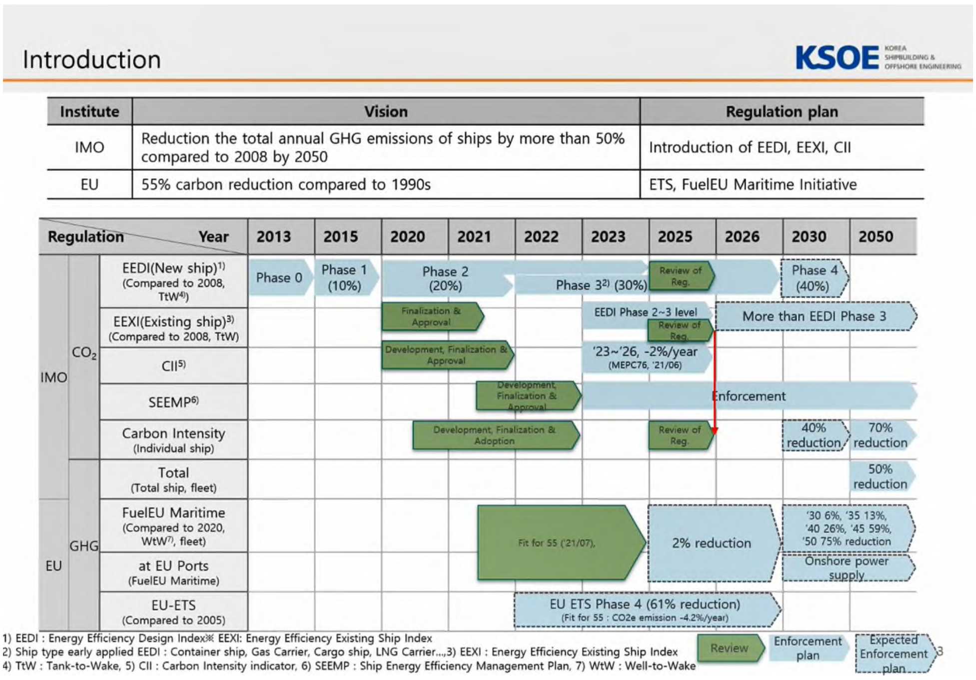



*Figure 27 Overview of greenhouse gas emissions regulations.*

## Solutions for $NO_X$ control

*This section was written by DTI, Denmark*

The emissions of $NO_x$ from marine engines can comply with IMO Tier III with three different basic strategies:

- EGR, which is only effective and sufficient for IMO Tier III compliance on 2-stroke engines.
- SCR, which can be used for Tier compliance on both 2-stroke and 4-stroke engines.
- Alternative fuel types can be used to reach Tier III compliance in combination with EGR or SCR.

It is important to note that most engines with IMO Tier III approval are designed for operating in either IMO Tier II or Tier III mode. The relevant Tier III engine technology, engine settings, emission after-treatment and fuel types are usually switched from Tier II to Tier III operating mode when entering an ECA zone.

### EGR – exhaust gas recirculation

EGR is widely used for Tier III compliance on 2-stroke engines.

EGR is a system that recirculates some of the exhaust gas back into the cylinders. The specific heat capacity of the water and $CO_2$ in the recirculated exhaust gas is higher than that of fresh air. The higher heat capacity of the scavenging air is effective in lowering combustion temperature and hence the $NO_X$ formation.

The main reason for using this on 2-stroke engines is that they operate with a large surplus of combustion air and can tolerate a large ratio of EGR to fresh air. In addition, they are allowed to emit more $NO_X$ per kWh than 4-stroke engines.

2-stroke engines can be delivered with EGR installed, or partly prepared to have the EGR systems installed if the ship is later assigned for operation in or through ECA zones.

The implementation of the EGR can be quite complex since the pressure of the EGR gas is lower than the pressure of the scavenging air. The system therefore requires an extra blower, in addition to several gas valves that open or close when the operating mode is changed. Furthermore, the gas must be cooled with a water spray and a heat exchanger, water droplets must be removed by a mist catcher, and the gas reintroduced by a blower and mixed with inlet air.

EGR circuits will generally be used only in Tier III mode, but it is also possible to have a permanently open, but variable, EGR circuit for some engine configurations.

In 4-stroke engines, EGR cannot be used effectively to reduce $NO_X$ to the compliant level in IMO Tier III. These engines must use either alternative fuel (LNG) or be equipped with SCR.

### SCR – Selective Catalytic Reduction

With the introduction of IMO Tier III emission standards for new marine vessels operating in ECA zones, SCR has become a standard solution for IMO Tier III compliance on 4-stroke engines, as well as some 2-stroke engine designs.

#### Background

The SCR principle was originally developed for automotive applications, to meet stringent US EPA and Euro standards for NOx emissions. In the early tests of the technology, it was found that the fuel sulfur in diesel fuel for road transport could cause problems with clogging of the catalysts. This caused the allowable fuel sulfur content to be reduced to the present 10 ppm. Considering that marine fuel can contain up to 0.5 % (5000 ppm) sulfur, using SCR for ships is more complicated, and generally requires close attention to problems related mainly to formation of ammonia bisulfate.

### Operating principle

The basic solution consists of a dedicated SCR catalyst in combination with urea or ammonia dosing, which is controlled and adjusted with downstream and upstream $NO_X$ sensors, to maintain a low $NO_X$ concentration in the exhaust.

The SCR unit reduces $NO_X$ in a catalytic process, in which ammonia ($NH_3$) reacts with NO and $NO_2$ to form nitrogen ($N_2$) and water. The ammonia can be supplied as pure $NH_3$ or dissolved in water, but the most common approach is to use urea, $CH_4N_2O$, dissolved in water. This solution is sprayed into the exhaust gas upstream of the catalyst. The water evaporates and the urea decomposes and reacts with water to form $NH_3$, which is adsorbed onto the catalyst surface. NO and $NO_2$ then react with $NH_3$ on the catalyst surface. The nitrogen oxides are reduced as the nitrogen reacts to form free nitrogen ($N_2$) while hydrogen and oxygen forms water ($H_2O$).

### Efficiency

The SCR catalyst must provide a reduction of approx. 80 % compared to Tier II emission standard to reduce $NO_X$ emissions to Tier III level, when measured and weighted in accordance with the procedure described in $NO_X$ Technical Code 2008.

The $NO_X$ reduction efficiency increases with exhaust gas temperature, as the catalyst activity increases. Very high efficiency, typically above 90 %, is possible from around 300-350 C, meaning that the $NO_x$ reductions can reach the required level, even if reduction is not possible at the lowest load under test conditions.

SCR systems are typically only active when the engines are in Tier III mode, as they must be inside ECA zones. Outside the ECA zones, SCR systems are typically disabled, and the engine operate in Tier II compliance mode. This saves the cost of reducing agent (urea or ammonia dissolved in water) and extends the lifetime of the catalyst and service intervals.

The SCR is not effective against other pollutants than $NO_X$. With ammonia as a future fuel option, the SCR will however be effective for reducing ammonia slip.

Reduction of laughter gas ($N_2O$) is currently problematic to achieve with SCR technology. The main reason is that $N_2O$ is a very stable molecule, which requires a higher temperature than $NO_X$ to be reduced efficiently. Catalyst developers such as Haldor Topsøe and Umicore are developing catalysts that enable efficient reduction of $N_2O$ at normal exhaust temperatures. There is however a general lack of knowledge on ammonia engine exhaust composition and no engines with ammonia as fuel in operation, to support this development.

### SCR on 2-stroke engines

In 2-stroke engines, SCR catalysts can be implemented as either a low-pressure SCR or a high-pressure SCR. The low-pressure SCR is mounted after the turbocharger outlet and can be used in combination with low sulfur fuel (≤0.1 %) only. The high-pressure SCR is mounted between the exhaust receiver and turbocharger, which increases operating temperature. This allows operation with higher sulfur fuel levels. These limitations are related to risk of ABS formation.

### SCR on 4-stroke engines

With 4-stroke engines, SCR is the only solution capable of ensuring a consistent $NO_X$

reduction to the levels required in IMO Tier III. The only current alternative is to use LNG in DF or monofuel (SI) engines, which are also IMO Tier III certified.

4-stroke engines use low pressure SCR systems only. ABS formation is avoided mainly by avoiding urea dosing below well-defined exhaust temperature limits.

### Ammonia bisulfate (ABS) formation

Formation of solid ammonia bisulfate (ABS) in and after SCR catalysts is a concern when using SCR systems in combination with marine fuels, which generally contain high levels of sulfur.

The sulfur contained in the fuel burns to form mainly sulfur dioxide. Under certain conditions, the sulfur dioxide can react with ammonia to form ammonium sulfate and bisulfate, which can condense on the surface of the catalyst at low operating temperatures.

Condensation of ABS will eventually fill and block channels of the SCR, such that the exhaust back pressure increases. If not controlled, the ABS will eventually result in severe back pressure which may cause the engine power to be reduced. ABS accumulation is however a reversible process since ABS will decompose back into $SO_2$ and $NH_3$ at higher exhaust gas temperatures. The ABS formation can therefore be controlled either by ensuring that exhaust temperatures are above the dew point of ABS, or by periodic elevation of exhaust gas temperature to decompose and remove formations of ABS in the SCR.

ABS formation may also occur in exhaust gas boilers, in which the exhaust gas transfers heat to the boiler. This may require periodic removal of ABS from the boiler to maintain the heat transfer at an acceptable level.

The condensation occurs at the dew point of the ABS, which is generally a function of the species ($SO_2$ and $NH_3$) concentration and catalyst temperature. Formation may occur below 280 °C with the use of 0.1 % sulfur. Figure 28 shows the required temperature for $NO_X$ reduction as function of sulfur content and operation pressure. Below these temperatures, adding urea or ammonia to the SCR will result in formation of ABS.

The risk of ABS formation makes the SCR solution more complicated to implement with high sulfur content. If ABS formation cannot be avoided, the crystalline buildup can still be controlled by periodic heating of the catalyst, which causes evaporation of the ABS.  This, however, requires additional heating in the exhaust, which can be provided by burners.

### Urea crystallization

Urea dosing is generally not possible below approx. 230 °C, due to the risk of urea crystallization before and in the SCR. If the temperature is too low, evaporation of the spray is inefficient and prevents the urea from being transported to and dispersed onto the catalyst. The crystalline formation can block the catalyst, which then requires disassembly for cleaning or exchange of the catalyst substrate, if cleaning is not possible.

Crystalline formation risk can be avoided if hydrous or pure ammonia is used, since it does not form these crystal deposits. Operating temperature can then be extended down to approx. 200 °C. Ammonia is, however, a highly toxic substance which requires extensive safety precautions. This limits the potential use of pure ammonia to cases where such precautions and crew competences are already in place, e.g., in ammonia carriers. If used as fuel however, ammonia will also be a feasible solution as reducing agent for $NO_X$ in the SCR.

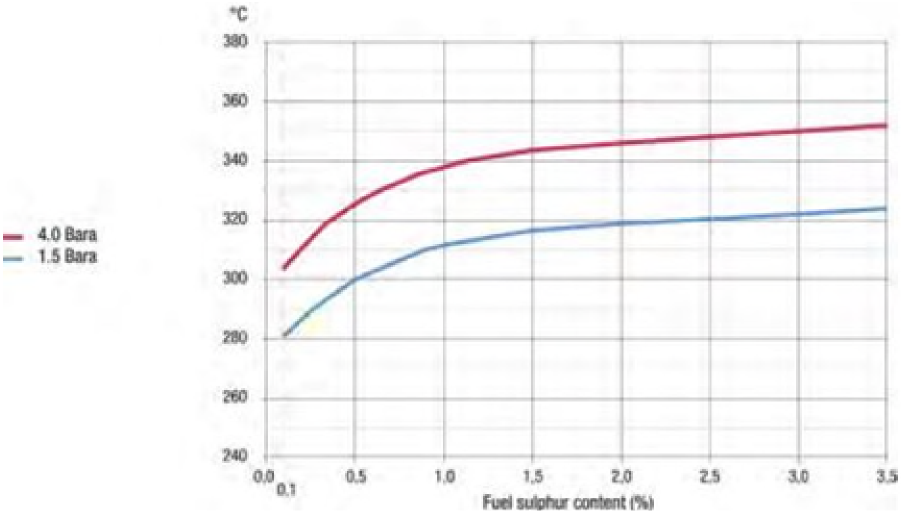



*Figure 28: Minimum SCR operating temperature as function of fuel sulfur content. Curves for high-pressure (red) and low-pressure (blue) SCR installations. MAN 2-stroke Emission Project Guide, 2022 (12.th edition)*

### Certification of SCR solutions

The market for SCR is currently supplied by a range of individual companies which are often specialized in catalyst technology. Engine designers cooperate with these suppliers to implement the SCR solutions on their engines.

The standard procedure for certification of a Tier III compliant engine is to demonstrate compliance in a test bench with the engine and SCR/EGR together. When type approved, engines in the same family can be sold with these systems as Tier III complaint. IAPP is issued after checking of parameters onboard according to $NO_X$ technical Code 2008.

Alternatively, SCR systems can be developed and tested in small scale in a separate setup under realistic operating conditions and then scaled up to full size for combination with a given engine. Tier III compliance is then demonstrated onboard the ship according to the verification procedure provided in $NO_X$ Technical Code 2008. This approach provides a faster path for IMO Tier III approval in the IAPP certificate.

### International Association for Catalytic Control of Ship Emissions to Air

This association with the abbreviation (IACCSEA) is an association of member organisations with common and shared interests in reducing $NO_X$ emissions from marine engines through selective catalytic reduction technologies. Members include industrial manufacturers and vendors of the SCR technology. The web site www.iaccsea.com provides some valuable insights in the early year's experiences with implementation of SCR for IMO Tier III $NO_X$ compliance.

## Solutions for sulfur control

*This section was written by DTI, Denmark*

The emission of sulfur dioxide caused by use of fuel oil in marine engines is regulated by MARPOL 1973/78 Annex VI. Amendments to this convention have made it possible to comply with regulation in two ways.

- Use of fuels with compliant levels of fuel sulfur
- Removal of sulfur from exhaust gas, to reach same levels as with compliant fuels.

The compliant concentrations for fuels are 0.5 % in global waters and 0.1 % in ECA zones. Alternative fuels such as LNG, LPG, LEG and methanol do not contain any fuel sulfur and may be used in solutions for sulfur compliance.

If the fuel used is not compliant in the ECA or globally, $SO_X$ scrubber must be used to reduce the $SO_2$ concentration in the exhaust gas. There are a variety of technical variations for scrubbers, but they all have the same performance requirement.

This chapter contains statistics for scrubbers, which have been found in the DNV Alternative Fuel Insight.

### $SO_x$ Scrubbers

The scrubber must reduce the $SO_2$ content as measured in the exhaust after the scrubber, to a level equal to or less than that which results from use of low sulfur fuel oil. The exhaust $SO_2$ concentration relative to $CO_2$ concentration must be below that in Table 9, which corresponds to the expected $SO_2$ concentration when using compliant fuel oil without scrubber.

*Table 9: Ratio of $SO_2$ to $CO_2$ with 0.5 and 0.1 % fuel oil sulfur content*

| Allowed fuel oil sulfur content (% m/m) | Ratio emission $SO_2$ (ppm)/$CO_2$ (% v/v) |
|---|---|
| 0.5 | 21.7 |
| 0.1 | 4.3 |

#### Operating principles

Marine scrubbers are in many cases constructed with vertical spray towers, in which the exhaust gas passes through a spray of droplets that absorb and react with the $SO_2$. Other types exist, but the spray tower is the dominating type.

Open loop scrubbers use sea water to wash out the $SO_2$ from the exhaust gas. After passing through the scrubber, the sea water is diluted with fresh seawater to comply with the IMO regulation for pollutant concentration in wastewater, before being discharged back to the sea. The discharge water is however generally believed to be harmful to sensitive ecosystems such as in near coastal waters and near harbors, which means that many states have banned the use of open loop scrubbers in their territorial waters. Closed loop scrubbers must instead be used.

Closed loop scrubbers utilize seawater with alkaline additives to reduce the $SO_2$ in the exhaust, by proper adjustment of process water alkalinity. The additives may be sodium hydroxide (NaOH) or magnesium hydroxide (MgOH). The closed loop scrubber system continuously filtrates the process water to separate the sludge, which is held onboard for disposal at port stay.

Hybrid scrubbers can switch between open and closed loop scrubbing, as required to comply with changing regulations along the route. This reduces the requirement for storage of accumulated sludge and alkaline reagents, as well as costs for waste treating and disposal.

### Efficiency against pollutants

Besides the intended removal of $SO_2$, scrubbers are also capable of reducing the emission of other pollutants in the exhaust gas, such as particulate (solid) matter, hydrocarbons and even $NO_2$, which is dissolved in water. There are however no regulations concerning these specific pollutants, and the fact that the scrubber can reduce them can only be considered an added benefit of the system, with very low associated costs.

The efficiency against particulate matter, and specifically black carbon, is considered to be limited (Controlling emissions from an ocean-going container vessel with a wet scrubber system https://doi.org/10.1016/j.fuel.2021.121323) with wet scrubber designs.

### Business case considerations for scrubbers

Considerations for use of scrubbers versus compliant fuels have been a very large dilemma for ship owners in recent years. Most concerns are related to the business case for each option, with many variables and large uncertainties affecting the outcome of the calculations.

Uncertainties concerning the fuel price development and in particular the price gap between VLSFO/ULSFO and HFO has made it difficult to predict if a scrubber solution improves the economy of operation. It is also important to note that scrubber installations are mainly economically relevant for large ships operating with HFO, whereas smaller ships will generally be in a better position with a change to compliant fuel.

Most ship owners have chosen to continue operation with VLSFO (ULSFO in ECA zones) rather than retrofitting scrubbers. This may partly be due to a restraining position considering the upfront investment and docking time required for installation of scrubbers. Other considerations may include the age and technical state of the ships, with newer ships generally providing more time for paying back the investment. Finally, the environmental impact of scrubbers has been debated heavily since the first installations were made, and the perceived risk of future restrictions on scrubber use may have prevented many from choosing this technology.

The business case for a scrubber installation is generally only considered acceptable with a payback time of no more than two years (Christensen). This may seem very shortsighted, but generally reflects the volatility of the shipping market in terms of fuel pricing, freight rates, contracting etc., which makes forecasting very difficult.

Except for some busy periods during the COVID-19 pandemic, the retrofitting capacity worldwide has not been a bottleneck for installations. During COVID-19, the situation was generally worsened by a lack of qualified work forces for retrofitting ships with scrubbers. This caused large delays in installations, which again meant that ships were in the harbors for a much longer time than predicted.

### Economy of scrubber installation

The costs related to a scrubber installation can largely be determined by installation and operating expenses, but the fuel price development is a large uncertainty with large impact on the payback time. The price difference between HSFO and VLSFO/ULSFO effectively determines the scrubber payback time. In the period 2019-2022, the marine fuel prices and the price gap (commonly named spread) has been subject to a large variation. Figure 31 shows the development since July 2019. In this time span, the price spread has varied from around 60 USD per ton to almost 400 USD per ton in August 2022. The recent increase in spread has improved the business case and created a large difference in competitiveness between ships with and without scrubbers. The increasing spread is a result of an increasing fuel demand and fuel price, which is caused by an increase in demand for marine transportation. In short, this means that operators with scrubbers have significantly lower operating costs and, in many cases, high revenues from contracts.

A case study performed by DNV-GL in 2018 have indicated that a price spread of 100 USD is required for a 20 MW open loop scrubber to have a payback time of 2 years (Sandal., 2018-10-10). Figure 29 shows the accumulated cost, which is highly dependent on the fuel price spread. The figure also shows that accumulated costs are estimated as only marginally higher for a hybrid scrubber system than an open loop scrubber system, with the consequence that the safest choice for shipowners would be the hybrid scrubber system. However, that has not been the case, as shown by statistics from DNV.

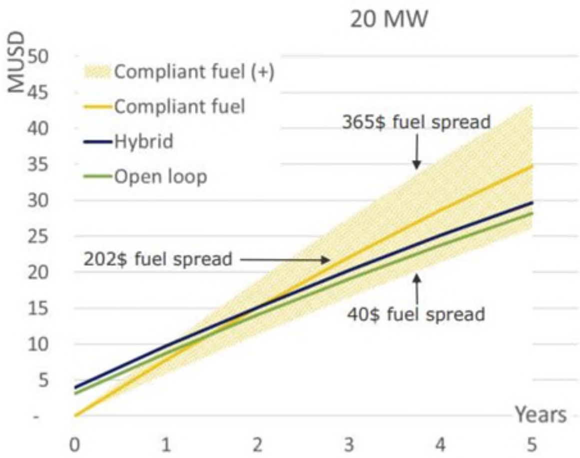



*Figure 29: Business case for a 20 MW scrubber. Y-axis shows accumulated operating costs. Source: (DNV-GL , 2018)*

The size of the ship (in terms of installed engine power) is also important. In general, large scrubber installations will provide larger savings, while small installations may be less feasible in terms of payback time. Figure 30 shows how DNV-GL has estimated accumulated 5-year costs for three installation sizes, with a fuel price spread of 200 USD. Despite the fuel price spread uncertainty, it clearly illustrates the potential fuel savings for large installations. It also illustrates that the installation expenses are much higher than the operational expenses.

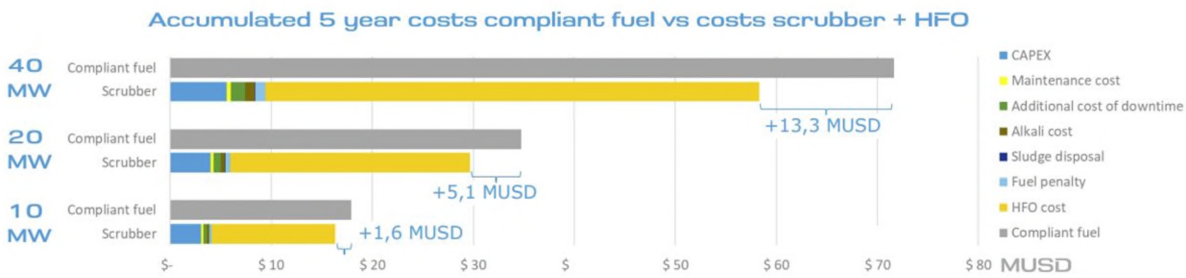



*Figure 30: Accumulated costs calculated for different scrubber sizes assuming a 200 USD fuel price spread. Source: (DNV-GL , 2018)*

Figure 31 shows the fuel prices and price spread since July 2019. The fuel price spread has been higher than 100 USD most of the time since 2021. Fuel prices were low while COVID-19 lockdowns resulted in a reduced demand for marine fuels, resulting in a lower price spread. Before that however, the price spread increased from 200 to 300 USD, peaking at the time of the 2020 global sulfur cap reduction to 0.5 %.

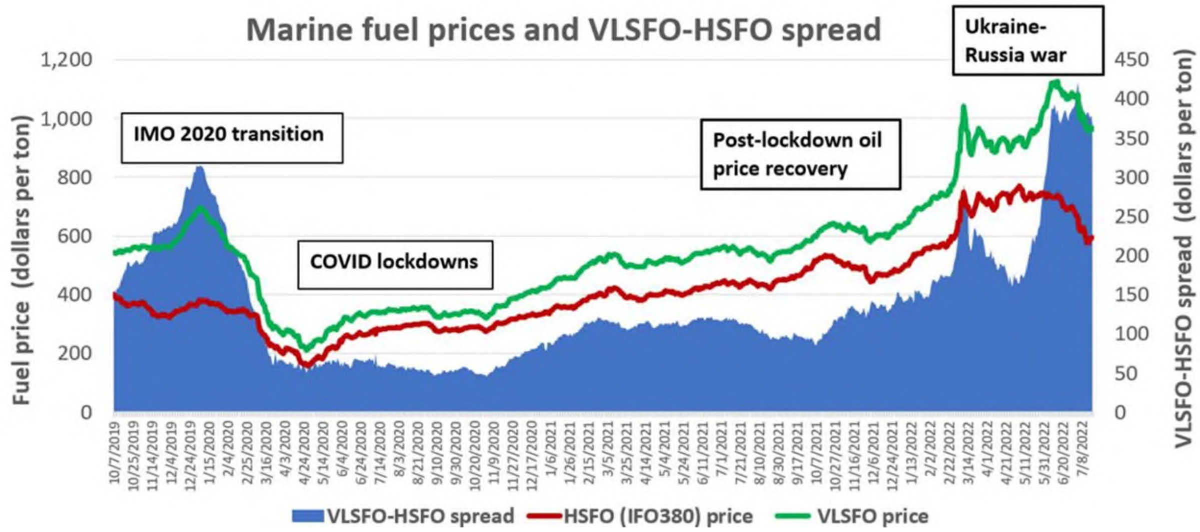



*Figure 31: HSFO/VLSFO Price gap development: Source: (Hellenicshippingsnews)*

### The development and adoption of scrubbers for ships

Marine scrubber systems have been developed building on the experience from flue gas desulfurization used on power plants, which have been subject to limitations in sulfur dioxide emissions for decades.

Guidelines for use of scrubber systems (ECGS) were defined by IMO in resolution MEPC.130(53), thereby accepting the use of scrubbers as an alternative to using LSFO from year 2005. At that time however, the global sulfur cap was at 4.5 % and the ECA sulfur cap at 1.5 %, so using compliant fuel in the ECA zones was a far better option than scrubbers, especially for ships operating only part time in the ECA zones. Ships entering the ECA zones would simply shift to fuel with 1.5 % sulfur held in separate fuel tanks onboard, to be compliant in the ECA zones.

### Important milestones motivating new scrubber installations

The tightening of permissible fuel sulfur in ECA zones from 0.5 % to 0.1 % effective from 2015 motivated a noticeable number of installations, such that the total reached 387 in 2017. Although the AFI statistics do not cover ship size and operating area, it is likely that most of these installations were performed on large ships operating mainly in or exclusively in the ECA zones, for which the fuel sulfur limit was lowered.

In 2016, following MEPC 70, IMO announced the decision to stick with the previously announced transition date (2020), at which the sulfur limit was to be reduced from 3.5 % to 0.5 % globally outside ECA zones. This motivated a larger number of installations starting from around 2017, in preparation for the 2020 deadline.

By the end of 2021, 4,539 of the existing approx. 57,000 registered ships above 1,000 DWT were registered as operating with scrubbers. It appears that the number of new installations will be low for the coming years, which indicate that the shipping industry is currently in a period with high revenue and a general reluctance to take ships out of operation for retrofitting of scrubbers, despite a historical high price spread on fuel oil which supports the business case.

According to the DNV AFI, about 67 % of ships operating with scrubbers have been retrofitted to existing ships, while 33 % of the installations are made on new ships.

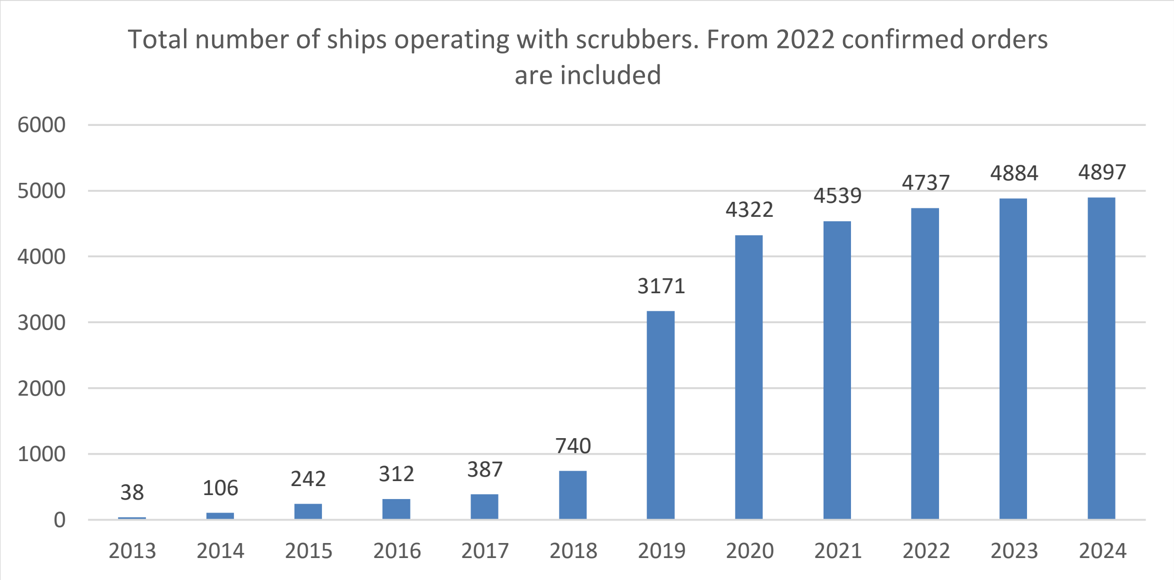



*Figure 32: Development in total number of ships with scrubbers since 2013. Data from (DNV Veracity, 2022)*

## Use of scrubbers on different ship types

The DNV statistics also specify the ship types on which the installations are made. Table 10 shows the number of installations for each ship type, together with data for total number of ships and the subdivision in main engine power categories. Numbers for distribution of ships have been provided by Danish Shipping, reported for September 2022.

To present a realistic view on the number of ships which can possibly be equipped with scrubbers, only ships above 5000 GT have been included. As such smaller ships can be equipped with scrubbers, but business cases have historically not been acceptable for engine sizes below 5 MW, and most scrubber systems are likely fitted to ships with engine power above 10 MW.

*Table 10: Total number of ships (2022) above 5000 GT, with main power subcategories.*

| Ship type | Total number of ships above 5000 GT | Main engine P < 10 MW | Main engine 10 < P < 40 MW | Main engine P > 40 MW | Ships with scrubbers | Percent of ships with scrubbers |
|---|---|---|---|---|---|---|
| General cargo ships | 3,229 | 3,085 | 167 | 0 | 113 | 3% |
| Vehicle Carriers | 761 | 87 | 674 | 0 | 54 | 7% |
| Liquified Gas tankers | 1,495 | 518 | 942 | 35 | 118 | 8% |
| Bulk carriers | 11,891 | 8,727 | 3,162 | 1 | 1,642 | 14% |
| Oil/chemical product tankers | 3,802 | 3,575 | 227 | 0 | 574 | 15% |
| Ro-Ro cargo ships | 1,265 | 274 | 985 | 6 | 195 | 15% |
| Container ships | 5,287 | 1,144 | 2,391 | 1,752 | 1,023 | 19% |
| Crude oil tankers | 2,945 | 158 | 2,787 | 0 | 682 | 23% |
| Passenger Cruise ships | 344 | 60 | 108 | 176 | 218 | 63% |
| Total numbers | 31,019 | 17,628 | 11,443 | 1,970 | 4,619 | |

The engine size categorization further serves to illustrate the general size distribution of ships with respect to propulsion power. Only very large container ships, LNG carriers and large cruise ships have more than 40 MW of propulsion power installed, and about half of all ships above 5000 GT have less than 10 MW of main engine power.

Cruise ships have a very high installation percentage compared to all other categories. This is likely due partly to the increased awareness of the health issues related to exposure to particulate matter, which has been in focus by researchers (Ryan Kennedy) and highlighted in various media since around 2019. Cruise ships are one of the few cases where fuel cost does not dominate the operational cost, since they generally carry a very large crew for supporting and serving passengers, often around 1 crew member per 2-4 passengers. The incentive for using scrubbers is therefore likely that operation with scrubbers improves the air quality for the passengers by removing a large share of the particulate matter pollution and reduce visible black smoke. Avoiding pollution in sensitive areas is likely also of great importance. Considering the engine power and fuel consumption of these ships, fuel cost savings are however also considerable, as many of the cruise ships will spend much time in either the North American or EU ECA zones.

### Scrubber technologies in use

The DNV AFI provides a simple statistic for the type distribution of scrubbers, which includes both operational and ordered scrubbers until 2024. Table 11 summarizes this statistic.

*Table 11: Scrubber types in operation and ordered until year 2024.*

| Scrubber type | Open | Hybrid | Closed | Unknown | Dry | Total |
|---|---|---|---|---|---|---|
| Number of ships | 3,987 | 814 | 68 | 23 | 4 | 4,896 |

The open loop scrubbers are likely used mainly in ships operating in deep sea shipping, since discharge of scrubber water is allowed in open waters according to IMO regulation. Hybrid scrubbers allow the operator to minimize operation costs at open sea with open loop seawater operation and change to closed loop fresh-water operation in areas where scrubber water discharge is prohibited. The closed loop systems are likely installed primarily on vessels operating exclusively on routes or in areas in which open loop scrubbers are not permitted.

Four of the systems in the statistics are dry scrubbers, a new technology in which sulfur reacts with a caustic powder, which is retained by a filter. The technology retains not only sulfur dioxide but is also very effective against particulate matter. The drawback of the technology is that the reactant powder is heavy and bulky, with considerable handling costs for replacement in harbor. The company Andritz is currently the only company offering this solution.

### Scrubber market actors

The production and installation of scrubbers for large marine vessels has created a large industrial market in the recent decade. Wärtsilä and Alfa Laval have each supplied around 600 scrubber systems, while more than 30 additional suppliers have delivered the rest.

### Exhaust Gas Cleaning Association

The Exhaust Gas Cleaning Association is funded by industrial members. The association provides a base for knowledge and experience sharing. The association also holds workshops and presentations on the use of scrubbers.

The website EGSCA.com provides an updated global map with information about specific rules for use of open loop scrubbers within territorial waters, ports and ECA regions. A notable regulation which is seen here is the coastline of China, in which it is now prohibited to use open loop scrubbers in their coastal waters. Besides, many ports prohibit or limit the use of open loop scrubbers, based on country specific legislation.

## Black Carbon reduction

*This section was written by ECCC Canada.*

In 2020, a literature search on Black Carbon (BC) and Particulate Matter (PM) emission factors used in emission inventories for different types of marine fuels, types of marine engines, operating conditions and emission control technologies was conducted. (ERMS 2021)

Along with the properties of BC emissions, their impacts, measurement methods, the activities of the International Maritime Organization (IMO) and the International Council on Clean Transportation (ICCT) related to marine PM and BC emissions, and the methodologies for arriving at emission inventories of BC emissions from marine sources, the results from 17 studies resulting from the literature scan were summarized. A comparison of the BC emission factors observed in these studies was made with the BC emission factor correlations in the Fourth IMO GHG Study. (IMO 2020)

The literature search reviewed studies conducted with BC or PM measurements from both on-board vessels and with test beds in laboratories.

Eleven on-board test measurement studies were reviewed and included:

- Heavy Fuel Oil (HFO) + scrubber use

  6 studies: 7 vessels (ferry, cruise ship, auto cargo and container)
- 0.5% S Very Low Sulfur Fuel Oil (VLSFO) use

  2 studies: 3 vessels (ferry, car and truck carrier)
- 0.1% S fuel use

  3 studies: 3 vessels (containers and supercontainer)

For the in-lab test bed studies, data is presented from six studies conducted at key research laboratories in Finland, Germany, Sweden, and the United States. Each of these studies used different engines, fuels, and loadings, along with different sampling and test methods for PM, PN and BC quantification and characterization. For each study, the literature review provides a summary of test engines and fuels, experimental set-ups, and results, conclusions and key messages.

Black carbon emissions and emission factors were entered the IMO GHG Study series for the first time in the Fourth edition in 2020, based on the emission factors developed by the ICCT. These emission factors have been presented in the overlapping reports by Comer et al (2017) and Olmer et al (2017a, 2017b).

The methodology derives its basic approach from observations by Johnson et al (2016) that apart from fuel properties the two factors that most strongly affect BC emissions from diesel engines are the type of engine (2-stroke vs 4-stroke) and the load (as a fraction of the maximum possible). Fuel characteristics are captured broadly as residual or distillate.

Filter smoke number (FSN, as measured by AVL 415S or AVL 415SE smoke meters) were used to quantify BC emissions in developing the correlations between emission factors, fuel type, engine type and engine load. Ultimately the developed correlations used data from 27 engines from tests conducted by Johnson et al (2016), Aakko-Saksa et al (2016) and the European Association of Internal Combustion Engine Manufacturers EUROMOT (2016). To establish emission factors that would be more representative of the emissions from the global fleet other factors were considered.

The 4th IMO GHG Study acknowledges the uncertainty involved in BC emission factors, but adopts this methodology as a step towards better understanding of trends:

*While the factors influencing BC emissions are not limited to engine type, fuel type, and engine load, these three parameters help understand the behavior of BC emissions in a manner that is useful for generating bottom-up emission inventories where these parameters are known. Other fuel parameters including the aromatic content and hydrogen content also likely influence BC emissions, but are out of the scope of this study. The BC emission factors in this study are based on measured Filter Smoke Number (FSN) values that have been then converted to BC mass using a mass absorption coefficient. While the BC fuel based emission factors have a degree of uncertainty and they can be improved over time, for the Fourth IMO GHG Study they are useful for understanding trends in BC emissions from ships over time. (IMO 2020)*

For this literature scan, most of the reviewed studies had reported the emission factors in g/kWh units, but the correlations mentioned above were based on g/kg fuel. Therefore, the conversions were made using the brake specific fuel consumption where reported, or the estimations used by Olmer et al (2017).

Even with the limitations with respect to the BC emission factor correlations comparisons of the data reviewed in the literature scan, with the emission factors from the IMO can be used to present a framework for highlighting the main characteristics of the data from different studies.

Olmer et al (2017) Appendix F, and Comer et al (2017) Appendix G provide a detailed description of the methodology by which an overestimation bias was introduced deliberately into the correlations. The justification for such an overestimation was based on:

- *Emissions from older in-service engines that may not be as well-maintained are expected to be higher.*

- *Laboratory testing was completed under steady-state conditions with constant, well controlled engine speeds. In contrast, emissions may be higher for real marine engines under transient conditions with continual changing wind and wave conditions.*

- *Emissions from modern Tier II and Tier III engines (which represented 74% of the fleet tested for the correlations) do not likely represent emissions from ships in the global fleet.*

- *Variations in fuel quality can influence BC EFs in the global fleet. In general, poorer quality fuels emit more BC than higher quality fuels. The test fuels available in Europe and North America may be of higher quality than fuels from other regions.*

Figures 15 to 18 present an overview of a selection of the BC emission factor data as a function of load, engine and fuel type from the studies reviewed. The emission factor correlations Omer et al (2017) are consistent with the trends observed across a reasonably wide range of studies, although they overestimate the emission factor values to a certain extent, particularly for residual fuels. These figures show that BC emission factors have been correlated with engine type (2-stroke vs 4-stroke) and load, with no reference to specific fuel sulfur content, and only a group reference (residual vs distillate) to fuel type in the 4th IMO

GHG Study. Low load conditions produced more BC emissions than operating at high load and residual produced more BC than distillate fuel.

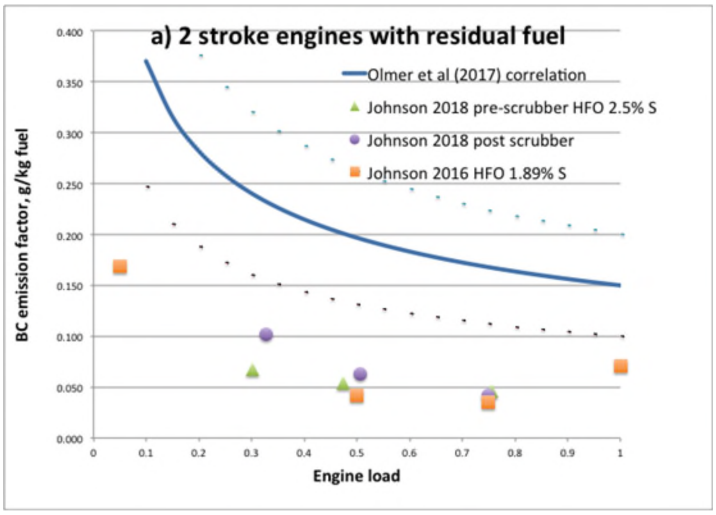



*Figure 33  Comparison of Black Carbon data with emission factors from 2-stroke engines with residual fuel*

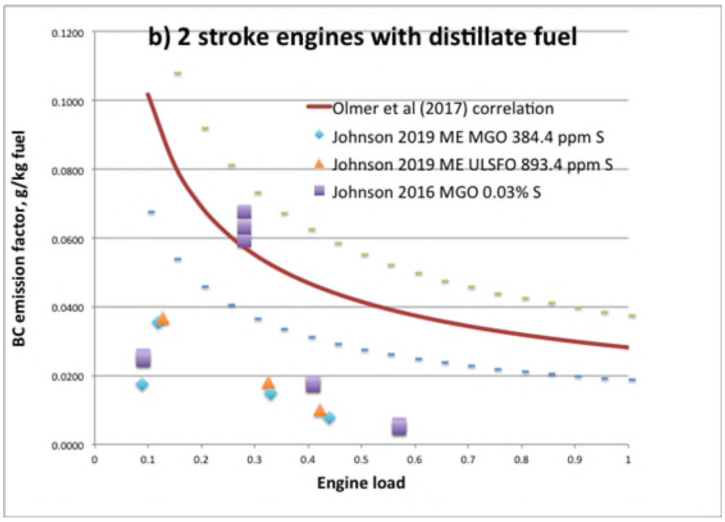



*Figure 34  Comparison of Black Carbon data with emission factors from 2-stroke engines with distillate fuel*

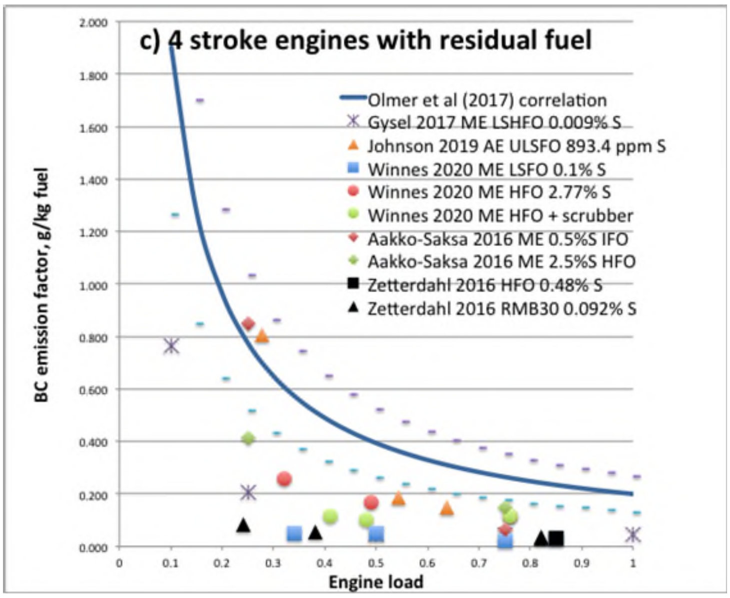



*Figure 35 Comparison of Black Carbon data with emission factors from 4-stroke engines with residual fuel*

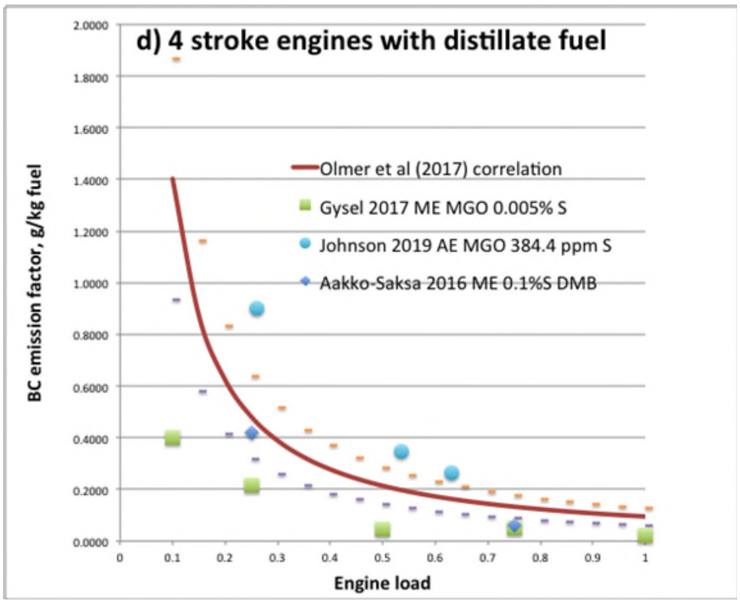



*Figure 36 Comparison of Black Carbon data with emission factors from 4-stroke engines with distillate fuel*

Figure 15 shows BC emissions increased after the scrubber (along with total PM) (Johnson et al 2018) It is suggested that the increase in sulfate species may be a result of a gas-to-particle conversion in the exhaust, but no explanation is offered for increases in BC. Johnson et al's (2016) data for the 2-stroke main engine data show an elevated value at 28% load (Figure 16), for which there was no explanation available, other than the vessel owner's comment that the 28% load point is not utilized in cruising except when switching between VSR (9% load) and regular steaming (57% load). The data have been presented in triplicate values to highlight the unexpected behaviour. Johnson et al's (2019) data for the 4-stroke auxiliary engine with MGO (384.4 ppm S) are noticeably higher (Figure 18) than the emission factor best estimate, in contrast to the data from the same engine with ULSFO (893.4 ppm S) in Figure 17.

In addition to the impacts of black carbon emission factors correlations, several observations were made with respect to the effects of scrubbers and fuel sulfur content on PM and BC emissions.

### $SO_2$ reduced to below 0.1% S equivalent.

All of the scrubber applications reviewed were able to meet not only the 0.5% S equivalent fuel requirement globally, but also the 0.1% S equivalent fuel requirement for ECAs, by reducing $SO_2$ emissions sufficiently, while using fuels that ranged between 0.65% S and 2.77% S. While the reductions were dependent on the sulfur content of the fuel, this is a significant result in that scrubbers can be used with HFO to meet regulations both inside and outside ECAs.

Scrubbers may deal with air emissions by removing pollutants from the gas phase to the liquid phase in either open or closed loop systems. Unless discharges to surface waters are tightly regulated, the possibility exists of creating one problem while solving another.

### BC reductions not clear

With the exception of one study, which reported PM and BC emission reductions comparable to gaseous emission reductions, BC emissions were not strongly affected by scrubbers, in fact showing an increase in one study. The increasing trend of BC emissions with decreasing load pre-scrubbers is also observed post-scrubbers, pointing to the absence of any strong effect by scrubbers.

### PN can be affected by both count and size distribution

Total particulate numbers were significantly reduced in some studies, although PN reductions did not necessarily coincide with PM2.5 reductions. The changes in particle size distributions are also of primary interest, as they affect both direct human health effects and the behavior of particles in the atmosphere. A shift to larger particles concurrently with the reductions have been observed.

### Fuel sulfur effects on PM and BC emission factors

Fuel sulfur content is correlated with emissions of PM mass due to the SO4 that ends up in PM but does not appear as a strong determinant of BC emissions per se. Engine type, load, maintenance conditions and other properties of fuel, such as metal content, seem to play significant roles in explaining the difference in emissions between fuels with different sulfur content.

In addition to the use of distillate fuels, the use of liquefied natural gas, biodiesel, HVO, methanol, hydrogen, ammonia have the potential to reduce black carbon emissions from marine vessels.

REFERENCES used in this section:

(Aakko-Saksa, 2016) , (Comer, 2017), (Karman, 2020), (EUROMOT, 2016), (Gysel, 2017), (IMO, Fourth IMO GHG Study 2020 – Final report, MEPC 75/7/15,, 2020), (Johnson K. M., 2016), (Johnson K. M., 2018), (Johnson K. P.-P., 2019), (Olmer N. B., 2017), (Olmer N. e., 2017), (Winnes, Moldanová, Anderson, & Fridell, 2016), (Zetterdahl M., 2016).

## Particulate filters for marine applications

*This section was written by DTI, Denmark.*

Emissions of particulate matter (PM) from ships, including black carbon (BC), constitute a significant contribution to air pollution. This pollution has negative effects on human health, especially in coastal waters and near cities.

Due to the composition of residual fuel oils with high sulfur concentrations traditionally used in shipping exhaust gas, it is however a problem which is difficult to solve with technologies used for road and non-road applications.

The use of low sulfur distillate fuels and alternative fuels such as LNG greatly reduces the particulate matter formation and may allow for the use of high efficiency particulate filters to be used on ships on which the air quality is of high importance.

### Particulate filter technologies

#### Ceramic wall flow filters

The most common technology today in use for vehicles is the closed filter type, technically named wall-flow filters. These filters are made of porous ceramic materials (either silicon carbide or cordierite), which are extruded to form monoliths with channels. By blocking channels in each end of the filter, the exhaust gas is forced through the porous filter wall. Particles adhere to the surface of the channels and the inside of the porous walls, which creates a highly efficient filtration, from 95 % to more than 99.9 %.

#### Fiber filters

Filters can be made with ceramic or metal fibers, which are woven or compacted to produce an efficient particulate trap. The metal fiber filter type can be regenerated by passing a current directly through it. Fiber filters can be as efficient as wall flow filters, but not as easy to purge for ash.

#### Partial or open filters

This filter type relies on particle retention mainly by thermophoresis as the exhaust gas passes through a filter material with a high internal surface area. Efficiency can be from 50 to 80 %.

### Regeneration

The accumulated soot can be burned (oxidized) either by ensuring a sufficiently high exhaust temperature (600-700 °C) or at lower temperatures (330-400 °C) if the filter is coated with a catalytically active coating.

The exhaust gas temperature can be elevated before the filter with diesel injection onto an oxidizing catalyst (DOC) which oxidizes the fuel. The DOC can also be used to convert NO to $NO_2$, which is more active in soot oxidation than oxygen. It is however important that the DOC is sulfur tolerant.

Alternative methods for increasing exhaust gas temperature for regeneration is to use an external burner or an electrical air heater in front of or around the filter. These options are very energy consuming, and it can be an advantage to use them for regeneration when the engines are not in use, such that the exhaust flow is not carrying away the energy supplied to the filter.

### Fuel sulfur tolerance

In marine applications, the DPF coating must be sulfur tolerant. Conventional noble metal coatings, such as platinum, are very sensitive to sulfur and will be deactivated by sulfate formation, which builds up at low temperature. Other coatings, such as base metals, are therefore required to ensure appropriate sulfur tolerance. Such coatings are developed and are available through companies such as Haldor Topsøe, Umicore, BASF and other companies who specialize in catalysis.

### Ash accumulation

Wall flow and fiber filters retain not only soot, but also the ash from the combustion of both fuel oil and lubrication oil. Wall flow filters used for vehicles are normally able to accumulate ash corresponding to 250.000- 300.000 kms of use, before the need to be purged of ash or replaced. With 4-stroke marine engines operating on transport diesel, ash purging may be required annually, and require that the particle filters are dismantled.

Residual fuel oils contain a very significant amount of ash. Most 2-stroke engines are also designed to partially burn the lubrication oil that is used for cylinder liner lubrication, which also results in high quantities of ash, which is caused by the additives used to increase the base number (the ability to neutralize acid) of the oil. This presents a major challenge when considering particle filtration, especially 2-stroke engines, since it will require very frequent ash removal.

### Back pressure limitations

Back pressure is the term for the overpressure (relative to ambient) caused by flow resistance in the exhaust system after the turbocharger.

Marine engines of the 4-stroke design are equipped with carefully designed and matched turbochargers, which provide very high charge pressures to the engine. These large turbochargers are more sensitive to back pressure than the turbochargers in heavy duty engines, which can usually tolerate up to 25 kPa of back pressure. Marine engines are rarely specified for more than 10 kPa, and often less.

The reason is partly the loss of charging efficiency which effectively reduce available engine power, but also because the smaller pressure drops means that the turbos are exposed to higher exhaust temperatures and bearing loads, which can cause excessive wear, damage, or total failure in short time. To avoid exceeding the back pressure limit, filters must be dimensioned for lower pressure drops and higher soot/ash capacities, which again increases material costs of the DPF systems.

2-stroke engines are even more sensitive to back pressure. These engines operate with blowers that scavenge the cylinders, since there is no pressure difference to drive a turbocharger when the piston is in bottom position. If the back pressure is increased, the blower will require more capacity to ensure the same scavenging ratio. The capacity is however fixed, since the blowers are normally of the roots type, a fixed displacement type which is mechanically driven by the crankshaft. If 2-stroke engines are to be equipped with particle filters in the future, the engines must be designed to accept a higher back pressure than today.

The main challenge for 2-stroke engines may however be to ensure that soot is oxidized, and that ash is purged from the filters regularly. The exhaust gas contains large quantities of soot which need to be retained and oxidized in the filter, which is problematic since exhaust gas temperatures are rarely much above 300°C. In addition, combustion of fuel oil and lubrication oil creates a very high concentration of ash in the exhaust gas, and this ash must be purged from filters several times per day. This will require techniques that are not yet developed.

## Particulate filters available for 4-stroke marine engines

Standard ceramic wall flow particle filters can be used on marine 4-stroke engines, provided that the engines have a low lubricating oil consumption, such that the amount of ash from the oil does not accumulate in the particulate filter. The amount of fuel sulfur is critical to the choice of catalytic coating, which ensures that the filter can regenerate under normal operating conditions. Up to 50 ppm S, standard coatings used in DPF for road vehicles can be used. At higher sulfur concentrations, sulfur tolerant coatings are required to ensure that the particle filter can regenerate.

A few companies in the EU are constructing and installing particle filters for large marine 4-stroke engines. These are mainly intended for use on inland waterway boats such as in Holland, or other places in which local regulation sets higher standards for PM emission from ships. In Holland, tenders for construction which include water transportation of materials such as concrete and cement, has encouraged the installation of particle filters and SCR solutions as retrofits on older ships, by an incitement structure that awards reduction of emissions in the supply chain.

## Operating experience with particulate filters on ships

In 2014, Haldor Topsøe presented a particle filter system called Eco Jet, which is designed for 4-stroke engines operating on HFO, at that time up to 4.5 % S. This solution was demonstrated on the cruise ship M/S Queen Victoria from 2015, with filtration efficiencies around 80-90 %. The system is based on a wall flow filter with a sulfur tolerant which enables passive soot regeneration at temperatures below 400 °C. The system employs a method called “reverse pulse” for periodically purging ash and soot from the filter.

Danish Technological Institute has participated in two demonstration projects, in which particulate filters have been mounted on ships.

The first demonstration project started in 2014 on the Danish ferry M/F Ærøfærgen, which had one of two main engines retrofitted with a DPF. This solution used electrical heating for daily regeneration after the last trip, with engines stopped. The filter monoliths were later upgraded to include an integrated SCR filter coating, with urea as reducing agent. The DPF demonstrated more than 99 % reduction in PM, but there was considerable leakage through filter bypass valves which in some cases reduced overall filtration to less than 90 %. NOx reduction was found to vary from 40 % down to 20 % during the day, as the DPFs were filled with soot, and hence this integrated solution was performing much less efficiently than if the SCR was installed as a separate unit after the DPF, in which case reductions above 80 % could be expected.

The second demonstration project started in 2017. The first ship in this project, M/F Isefjord, had its 2 main and 2 auxiliary Tier II engines fitted with catalytic particulate filters in 2018 by the company Exilator ApS. The ship uses MGO, 50 ppm S as fuel. The filters on the main engines regenerate in operation as temperature increases to around 400 °C. Filters on generators are regenerated weekly by increasing the load on the engines. The filters have been in constant operation with ash removal once per year. A second ship has been selected for demonstration of a sulfur tolerant system with DPF and SCR, designed and built by the company Purefi A/S. The system is designed for operation with 1000 ppm fuel sulfur and the intention is to demonstrate IMO Tier III compliance, as well as EU Stage V for inland waterways. Due to delays, the system has not yet been installed and tested on this ship, but similar systems are now in operation.

## Control of GHGs and other emissions simultaneously

*This section was written by Päivi Aakko-Saksa, VTT. Reference:* (Aakko-Saksa, P. T., Lehtoranta, K., Kuittinen, N., Järvinen, A., Jalkanen, J.-P., Johnson, K., Jung, H., Ntziachristos, L., Gagné, S., Takahashi, C., Karjalainen, P., Rönkkö, T., and Timonen, H., 2023)

Warning messages on climate change are becoming increasingly serious and all possible actions are needed to address this threat. The International Maritime Organization (IMO) has an ambitious strategy to cut the shipping sector's carbon intensity by up to 40% by 2030 and 70% by 2050 in comparison to 2008. Ship emissions have harmful effects on climate, air quality, human health and the environment. Estimates indicate that shipping causes approx. 250,000 premature deaths and 6.4 million childhood asthma cases annually, since ships travel near densely inhabited coastal areas. This study carried out by researchers from Finland, the U.S., Greece, Canada and Japan (see reference in the end) focused on how fuels and technologies impact greenhouse gas and other harmful emissions from ship engines, and which are the best solutions to reach the goal of zero-emission shipping. Ship fleets are diverse (Figure 37), and the optimum solutions depend on the ship, route and region.

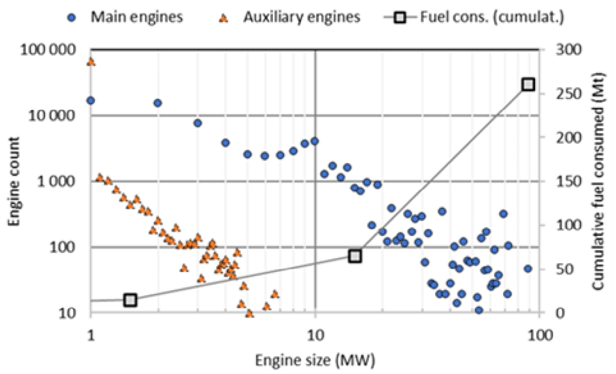



*Figure 37 The global fleet includes over 128,000 IMO-registered vessels with engines of many sizes.*

*A small number of large ships consume over 70% of marine fuels and emit the majority of global ship emissions. These ships typically have 2-stroke slow-speed diesel engines larger than 20 MW. Medium-speed diesel (MSD) 4-stroke engines consume 19% of marine fuels globally.*

**The carbon-neutrality of fuels** depends on their GHG emissions, including carbon dioxide ($CO_2$), methane ($CH_4$), and nitrous oxide emissions ($N_2O$). Non-gaseous black carbon (BC) emissions also have high global warming potential (GWP). Carbon-neutral fuels produced from biomass, waste or renewable hydrogen and captured $CO_2$ have the potential to substantially contribute on reducing ship emissions. Hydrogen gas technologies, batteries and ammonia options are not currently available for large ships and their feasibility will be seen.

Fuel technologies are of the primary importance, when dealing with GHG emissions from shipping, since the demand for energy in the maritime sector is expected to remain at approximately 310 Mtoe in 2050 despite of substantial energy efficiency improvements achievable by e.g. design, waste heat recovery, alternative maritime routes, regional trade, and shifts to rail cargo. Biofuels could be increasingly directed to shipping and aviation as road-transport switches to batteries. However, the quantity of compliant fuels may fall when they have to meet stringent criteria, such as RED II. This makes renewable hydrogen-based e-fuels an interesting option for shipping along with the increasingly available renewable electricity (Figure 38).

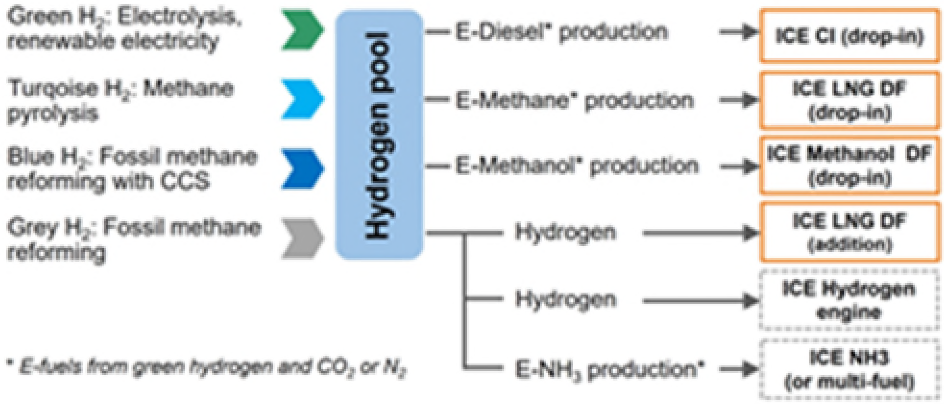



*Figure 38 Hydrogen pathways for ICE include fuels compatible with common diesel and gas engines : hydrogen-based e-fuels as drop-in.*

**Demand for carbon-neutral fuels is high due to existing and future emission regulations and zero emission targets.** This is especially true for products resembling current fossil marine fuels (diesel, LNG or methanol) that are compatible with proven technologies as “drop-in” fuels. Combining carbon-neutral drop-in fuels with efficient emission control technologies would enable (near-)zero-emission shipping and could be adaptable in the short- to mid-term. Methane, methanol, diesel-type molecules are all acceptable if they are carbon-neutral and meet sustainability criteria. Hydrogen-based e-fuels could become important building blocks in the transport sectors where other forms of electrification are difficult. E-fuels could also act as renewable grid storage, thus accelerating the transition to renewables. However, the viability and production of carbon-neutral raw materials are limited in the short term, and fossil fuels may be used for longer than desired, which makes carbon capture on-board ship an interesting option.

**The need to remove harmful emissions is emphasized.** Emissions that are harmful to health or the environment must be removed by means of fuel, engine or exhaust after-treatment technologies. Harmful emissions include nitrogen oxides ($NO_X$) and sulfur oxides ($SO_X$), which are regulated at this time, as well as emissions likely to be regulated soon. These are black carbon (BC) and methane emissions (Figure 39). Other harmful emissions are ammonia ($NH_3$), formaldehyde, particle mass (PM) and number emissions (PN). Black carbon emission (Figure 40) contributes to global warming and adversely affects health and the environment. The IMO has been studying the impact of BC emissions from international shipping in the Arctic since 2011. Reducing emissions may involve modifying the fuel, engine (or both), or adapting the exhaust after-treatment technology.

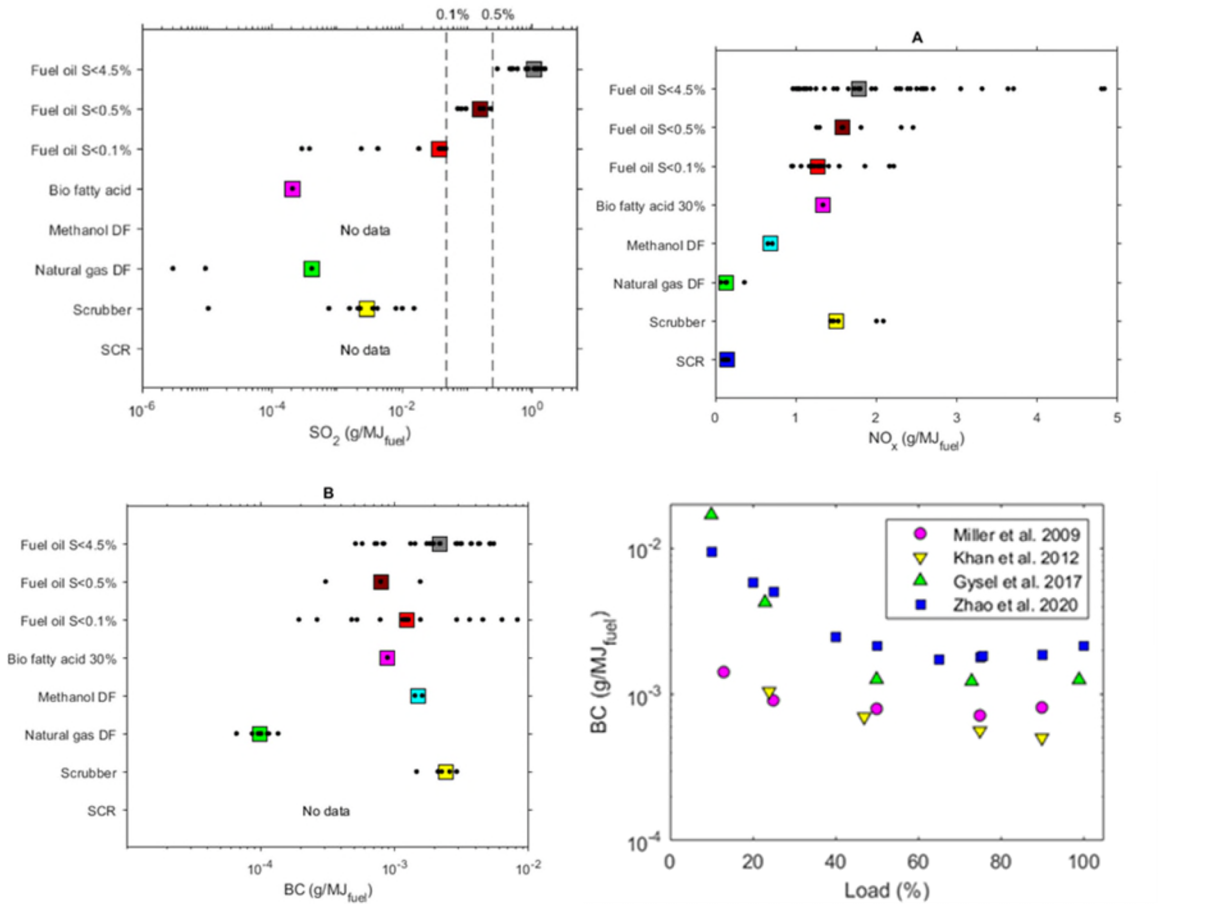



*Figure 39 BC, $NO_X$ and $SO_2$ emissions per MJ fuel*

a) BC emissions from marine engines using different fuels and exhaust gas treatment technologies with MSD and SSD engines at engine loads equal or above 40% MCR. b) Relationship between BC emissions and engine load for four marine engines with maximum continuous power of 54.84 MW 94 1/min Miller et al. 68.5 MW, 97 1/min Khan et al. 6.7 MW 512 1/min Gysel et al. and 15.5 MW 88 1/min Zhao et al. All engines were operating with high sulfur residual fuel except in Gysel et al. with low sulfur (0.009%) residual fuel. (see references from Aakko-Saksa et al. 2023 *(Aakko-Saksa, P. T., Lehtoranta, K., Kuittinen, N., Järvinen, A., Jalkanen, J.-P., Johnson, K., Jung, H., Ntziachristos, L., Gagné, S., Takahashi, C., Karjalainen, P., Rönkkö, T., and Timonen, H., 2023)).*

Substantial investments are needed to introduce carbon-neutral fuels, but they will also provide savings by reducing the costs to society caused by harmful emissions. This justifies support mechanisms and investing in clean technologies. The benefits of carbon-neutral fuels include lower external costs, and the fact that drop-in fuels do not require new infrastructure for transport and delivery. Calculations indicate that the emissions from 260 Mtoe of residual marine fuel cause external costs of 433 billion euros annually. Those costs could be avoided by using modern marine engines, carbon-neutral fuels and the best exhaust after-treatment options. The external costs are probably underestimated when considering the recent natural disasters caused by climate change. Marine fuel choices are driven also by non-technical aspects, such as public acceptance, fuel availability and prices. Hence, evaluations and solid evidence are needed to guide decision-making towards the best choices for the future.

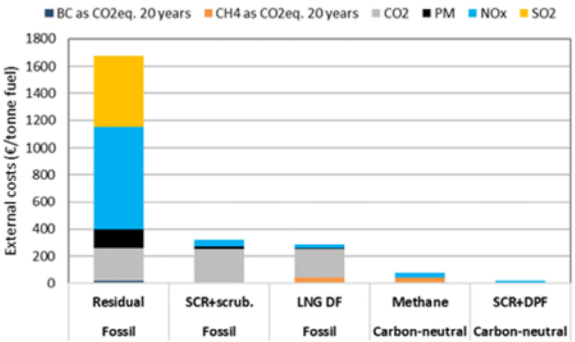



*Figure 40 Examples of external costs of ship emissions with selected technologies.GWP20 values were used for methane and BC emissions.*

No clear "winning" fuel was found in an evaluation of the three e-fuels (e-methane, e-methanol and e-Diesel) with fossil fuels and hydrogen/batteries as references (Table 1). The three options had equal scores for reducing emissions, although scores accumulated from different aspects. All these e-fuels, or respective biofuels, can be used in existing engines if carbon-neutral fuel production volumes increase.

*Table 12 Evaluation of impacts of assumed carbon-neutral e-methane, e-methanol and e-diesel as marine fuels with fossil and long-term references.*

| | $SO_X$ | $NO_X$ | PM, PN, BC | Other harm | GHG | Score |
|---|---|---|---|---|---|---|
| Fossil | | | | | | |
| HS | 0[a] | 0[a] | -- [b] | --[c] | -- | -6 |
| LS | +[d] | 0[a] | - [b] | -[c] | -- | -3 |
| LNG DF | ++[d] | +[a,d] | + [b,d] | -- [c] | - (21%) | +1 |
| Carbon-neutral, with renewable hydrogen and CCS/CCU [e] | | | | | | |
| e-Methane DF | ++[d] | +[a,d] | + [b,d] | -- [c] | + | +3 |
| e-Methanol DF | ++[d] | +[a,d] | 0[a] | - [c] | + | +3 |
| e-Diesel | ++[d] | 0[a] | 0[a] | 0 | + | +3 |
| H2-FC/batteries | ++[d] | ++[d] | ++[d] | --[c] | ++ | +6 |
| Ammonia | * | * | * | * | * | * |

[a] Available: scrubber, SCR. DPF for sulfur-free fuels = 0
[b] Developing: methane slip control, particulate filter, ESP. = -1,-2
[c] PAHs, heavy metals, formaldehyde, methane, infra need = -1, -2
[d] Low emission without exhaust aftertreatment =+1,+2
[e] Biofuels, depending on the production process, may resemble respective e-fuels in terms of their environmental impacts.
LS = sulfur content (S) <0.1%, HS = sulfur content >0.1%
*Not available at the time of writing. Notably, ammonia as fuel is not expected to emit $SO_X$, whereas e.g. $N_2O$ (a strong GHG) may be emitted.

Combining carbon-neutral drop-in fuels with efficient emission control technologies (also for retrofitting) would enable (near-)zero-emission shipping. This could immediately and simultaneously mitigate GHG and pollutant emissions. Substantial savings in external costs to society caused by ship emissions justify the regulations, policies and investments needed to support this development.

**Reference:** Aakko-Saksa, P. T., Lehtoranta, K., Kuittinen, N., Järvinen, A., Jalkanen, J.-P., Johnson, K., Jung, H., Ntziachristos, L., Gagné, S., Takahashi, C., Karjalainen, P., Rönkkö, T., and Timonen, H.: Reduction in greenhouse gas and other emissions from ship engines: Current trends and future options, Progress in Energy and Combustion Science, 94, 101055, 2023 https://doi.org/10.1016/j.pecs.2022.101055.

## $CO_2$ capture on board ships

*This section was written by LEC, Austria.*

Carbon capture on board a ship is feasible with pre-combustion and post-combustion concepts. Figure 41 shows a pre-combustion concept. (LEC - Large Engines Competence Center, 2023)

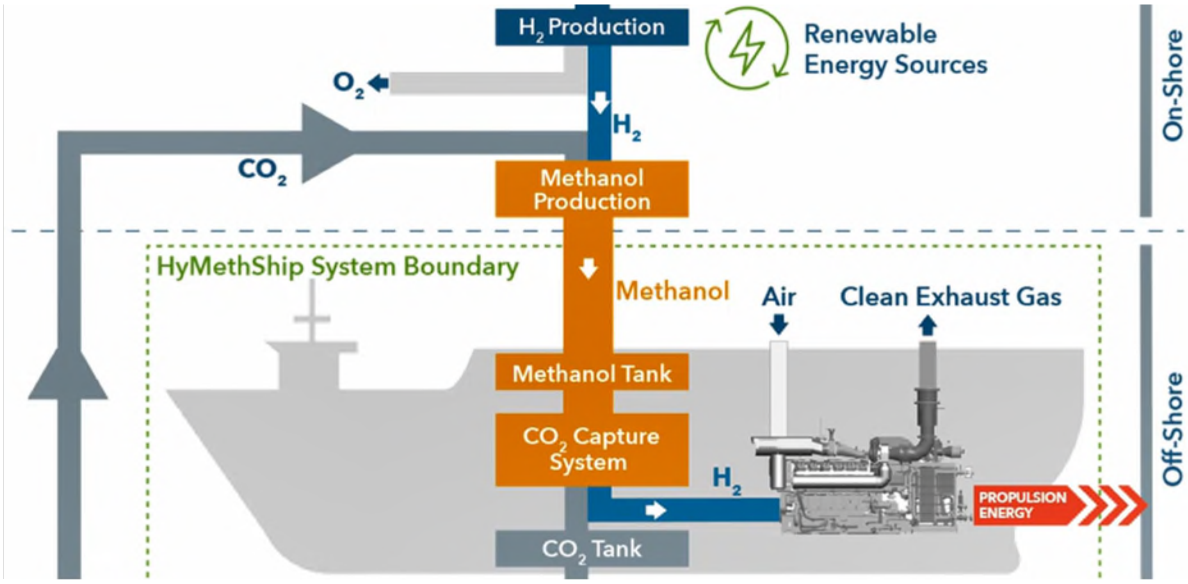



*Figure 41 Pre-combustion $CO_2$-capture concept for methanol ship (LEC)*

Post-combustion carbon capture was conceptualized in the FVV-project "CCS on Ships".

## Advanced biofuels and LCA

*This section was written by Mike Kass (ORNL); Troy Hawkins, F. Masum and Michael Wang (ANL); and Kevin Stork (DOE), USA.*

The United States Department of Energy has an ongoing research program devoted to assessing the economic and technical feasibility of biofuels for use in deep-sea marine sector.  This effort has centered on the use of bio-intermediates, which are oils derived from fast-pyrolysis (FP) and hydrothermal liquefaction (HTL).  These fuels are attractive since they can be derived from a wide feedstock range and are relatively low cost, prior to upgrading.  The work scope for this effort centers on the economics associated with production and operation, and the technical viability of the fuels along with their potential to reduce greenhouse gas (GHG) emissions.  A schematic diagram for these processes is shown in Figure 42.  In summary, bio-oil is produced via FP or catalytic FP (CFP) by rapidly heating dry feedstock to 500°C for 1-2 seconds.  The resulting bio-oils have high water and acid contents and must be upgraded to remove these components (and other oxygenates). A key feature of this process is that dry feedstock is required.  In contrast, HTL can process wet (high moisture) feedstock at more moderate temperatures, but high pressures are needed.  HTL bio-crudes also contain water and acids, but at much lower levels than bio-oils.  HTL bio-crudes are also known to have high viscosities.

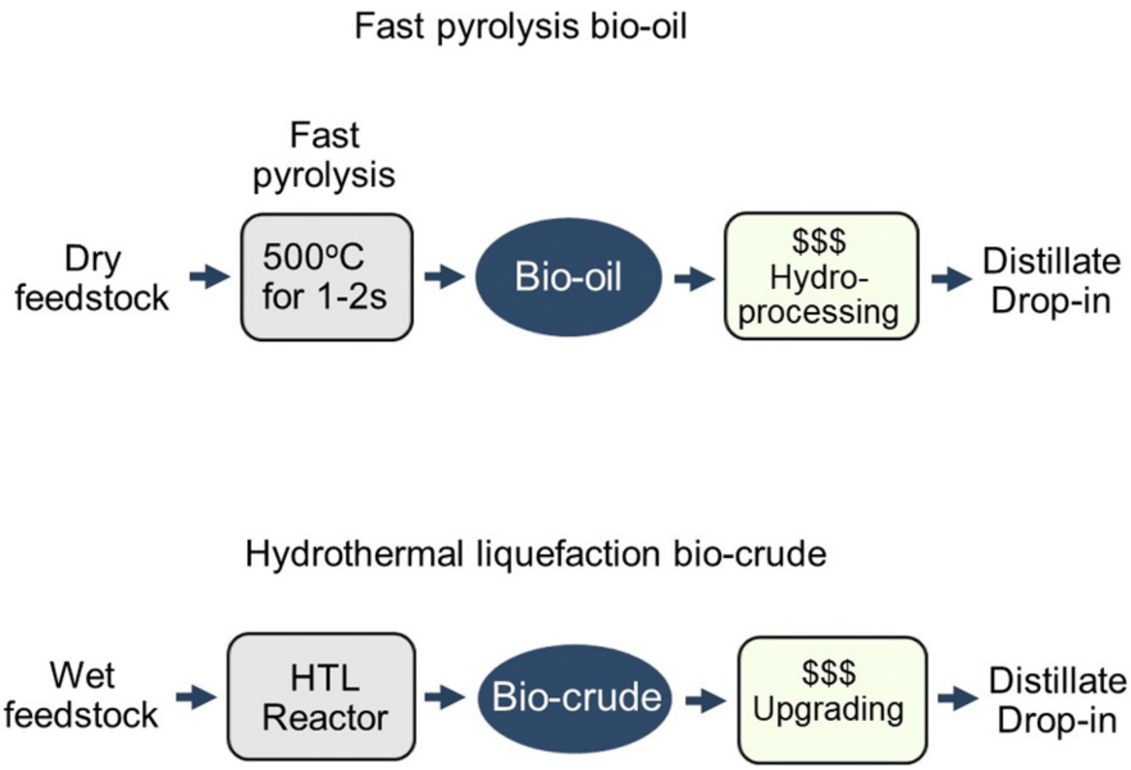



*Figure 42 Bio-intermediate production schematic via fast pyrolysis and hydrothermal liquefaction.*

The key technical concerns associated with biofuels are their compatibility with the existing infrastructure, combustion behavior, and blend stability.

## Bio-intermediate Studies

Compatibility here refers to both the impact of the fuels to the fuel system infrastructure and also the component handling. It is important that any new fuel chemistries (biofuel or otherwise) must be for stable blends with heavy fuel oils (HFOs). All HFOs contain asphaltenes which can precipitate out of solution when mixed with another fuel. It is important that the blends exhibit stability (or blend miscibility) during fuel change over to prevent filter plugging. For biofuels, this stability is especially important since these fuels are being introduced as blends with the HFO. Blend stability was evaluated for a CFP bio-oil and an HTL bio-crude using the ASTM 4740 protocols. A photo of the results (see Figure 43) showed that one CFP bio-oil demonstrated good blend compatibility with a very low sulfur fuel oil (VLSFO). However, it is important to note that CFP-based bio-oils were not able to pass the standard test for blend suitability. HTL bio-crude exhibited good compatibility when cosolvents were used or when the bio-crude was mildly hydrotreated.

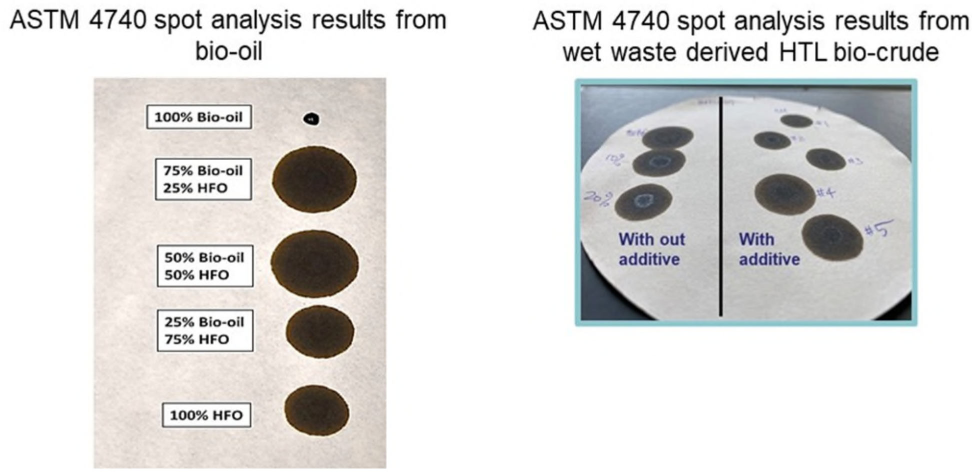



*Figure 43 Blend stability test results for CFP-based bio-oil and HTL-based bio-crude.*

Another important property is viscosity. It is important that the viscosity (or resistance to flow) of a biofuel must not be greater than the viscosity of HFO, since the fuel delivery system (especially the pumps) is designed to handle and inject HFO into the engine. Any viscosity increase of the fuel inside of the storage tanks or heated lines may cause compositional segregation and pumping difficulties. Of particular concern is the possibility of polymerization of CFP bio-oils, which are known to polymerize at temperatures greater than 60°C. The viscosity as a function of temperature was determined for bio-oils and bio-crudes as function of blend level with VLSFO. These measurements were conducted at 50°C and 90°C, which correspond to the temperatures inside the fuel storage tanks and downstream piping lines, respectively. The graphs in Figure 44 show the viscosity results at 25°C for CFP bio-oils and HTL bio-crudes. These curves show that the viscosity of the blend is reduced dramatically by small additions of CFP bio-oils and noticeable reductions occur with the HTL bio-crudes. These findings are significant since they indicate that the heating requirements to achieve proper viscosity of VLSFO are reduced with the two bio-intermediates. As a result, the energy needs are reduced and, thus, overall system efficiency is improved.

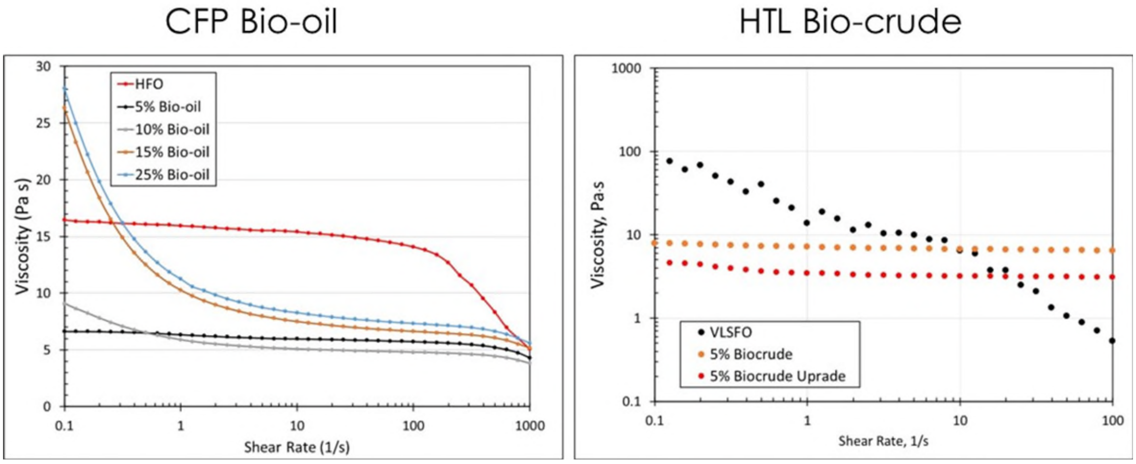



*Figure 44 Viscosity versus shear rate for blends of bio-oil and bio-crude with VLSFO at 25°C.*

The corrosion rate was also assessed for both CFP oils and HTL bio-crudes. HTL bio-crude results (while not presented here) showed that they were not corrosive to most steel grades. However, CFP bio-oils typically have high total acid numbers and the one used in this study was 112 mgKOH/g. In a recent study, ORNL evaluated the corrosion rate of a carbon steel, a Cr-Mo steel, and three stainless steel grades. These metals were exposed for 500 hours at 50°C in blends containing up to 50% bio-oil and 100% bio-oil. Both unstressed and stressed coupons were evaluated. The results are shown in Table 13. As seen in the table the corrosion rates are negligible for the fuel blends even at 50%. In contrast, the neat bio-oil caused significant corrosion in all of the metals except for the 304L and 316L stainless steels. The implication is that bio-oil blends up to 50% will not aggressively corrode fuel system metals.

*Table 13 Corrosion rate determinations for five steel grades as a function of bio-oil blend level in heavy fuel oil for 500 hours at 50°C.*

Corrosion rates (mil/yr) for blend levels and metal type

| Bio-oil content (mass%) | Carbon Steel | | 2.25Cr– 1Mo Steel | | 409 Stainless Steel | | 304L Stainless Steel | | 316L Stainless Steel | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 250h | 500h | 250h | 500h | 250h | 500h | 250h | 500h | 250h | 500h |
| 8 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 19 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 25 | 0.02 | 0.03 | <0.01 | 0.07 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 | <0.01 |
| 50 | 0.05 | 0.04 | 0.09 | 0.05 | 0.05 | 0.04 | <0.01 | <0.01 | <0.01 | <0.01 |
| 100 | 1.97 | 1.69 | 4.82 | 2.83 | 1.32 | 0.94 | <0.01 | <0.01 | <0.01 | <0.01 |

The combustion quality of these fuels was evaluated using the estimated cetane number (ECN) test for blends containing up to 15% of CFP bio-oil and up to 5% for both raw and upgraded HTL bio-crude. Higher blends were not possible due to limited sample quantity. The results are shown in Figure 45; ECN values higher than 17 are considered acceptable. The result show that the ECN values for the CFP bio-oil decreased with increased blend level, but acceptable combustion quality was achieved for blends containing up to 10% bio-oil. The ECN values for the HTL bio-crudes were also found to be acceptable. These tests have shown that both pyrolysis oils and HTL bio-crudes show promise as a marine fuel.

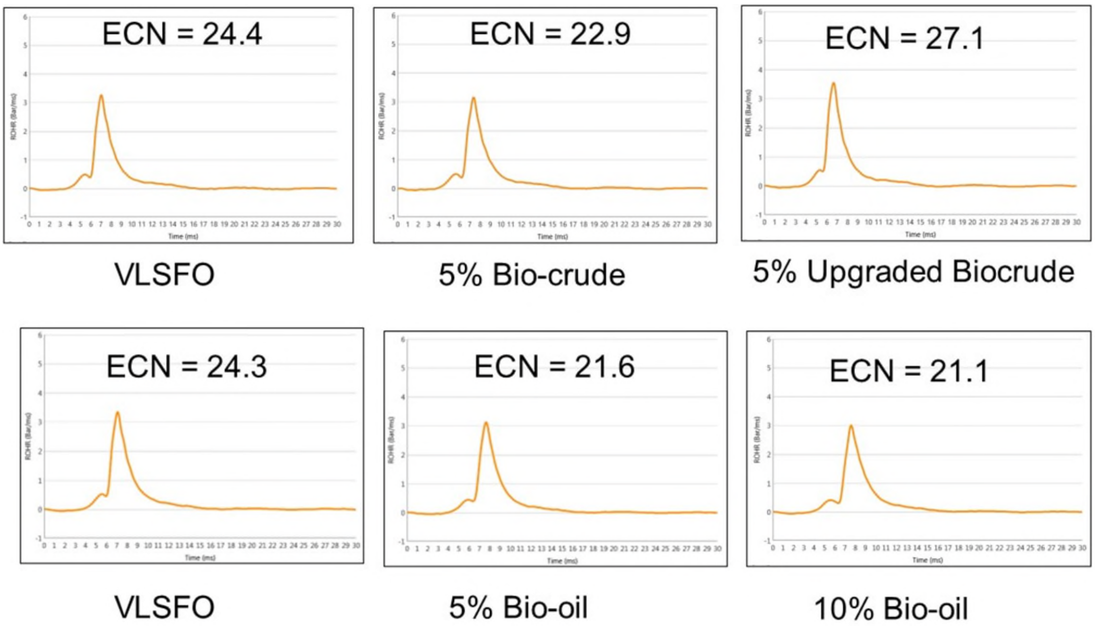



*Figure 45 Estimated cetane number results for HTL bio-crude (top) and CFP bio-oil (bottom) as a function of blend level with VLSFO.*

## Biodiesel Studies

ORNL also investigated biodiesel blends for their efficacy as marine fuels. As shown in Figure 46, biodiesel (when added at levels up to 25 wt%) showed excellent stability with VLSFO. In addition, as can be seen in Figure 47-Figure 48 both the lubricity (wear scar diameter) and viscosity of VLSFO were improved substantially with small additions of biodiesel. The addition of biodiesel was also shown to improve the combustion quality of VLSFO as can be seen by the increase in ECN with content in Figure 49. It is important to note that biodiesel and its blends with heavy fuel oil have been successfully demonstrated on cargo vessels and cruise ships.

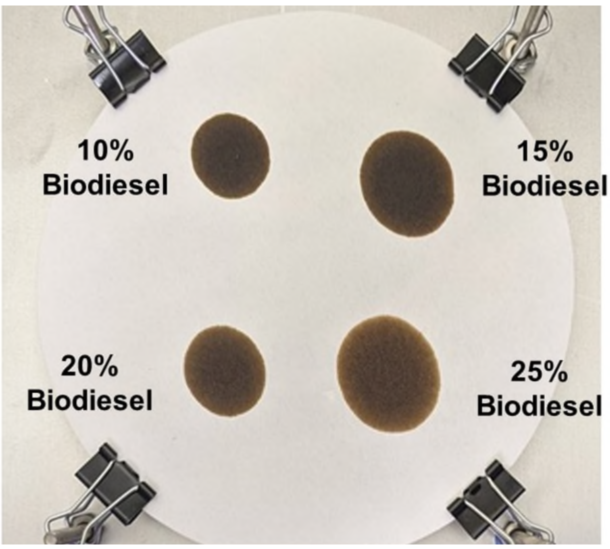



*Figure 46 ASTM 4740 test results for biodiesel blends with VLSFO.*

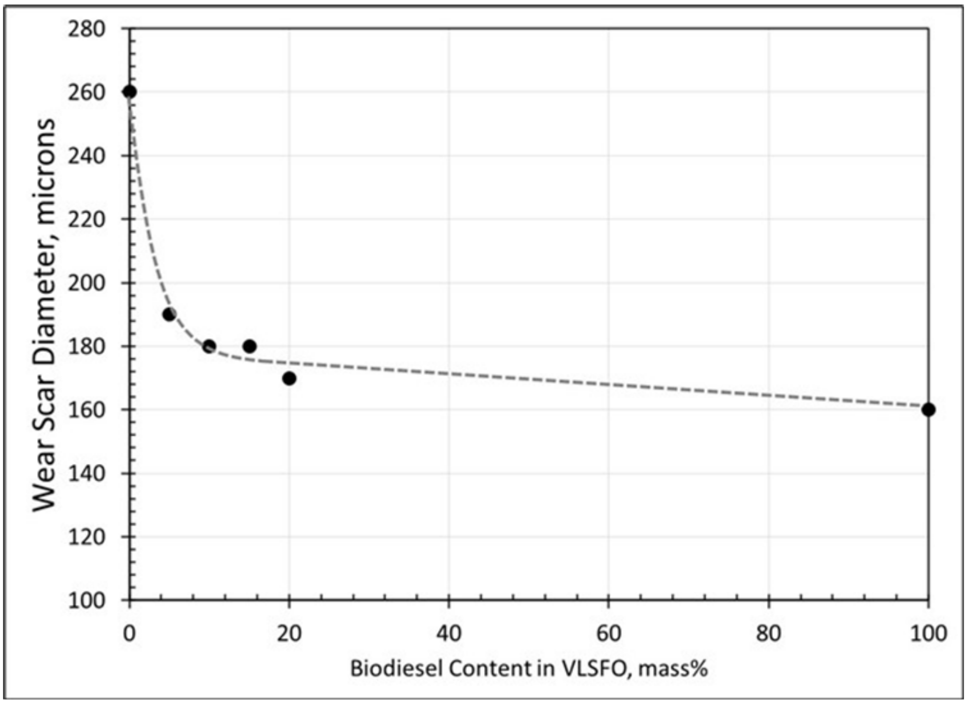



*Figure 47 Wear scar diameter measurements for biodiesel blends with VLSFO. Results show a significant reduction in wear scar diameter (improved lubricity) with added biodiesel.*

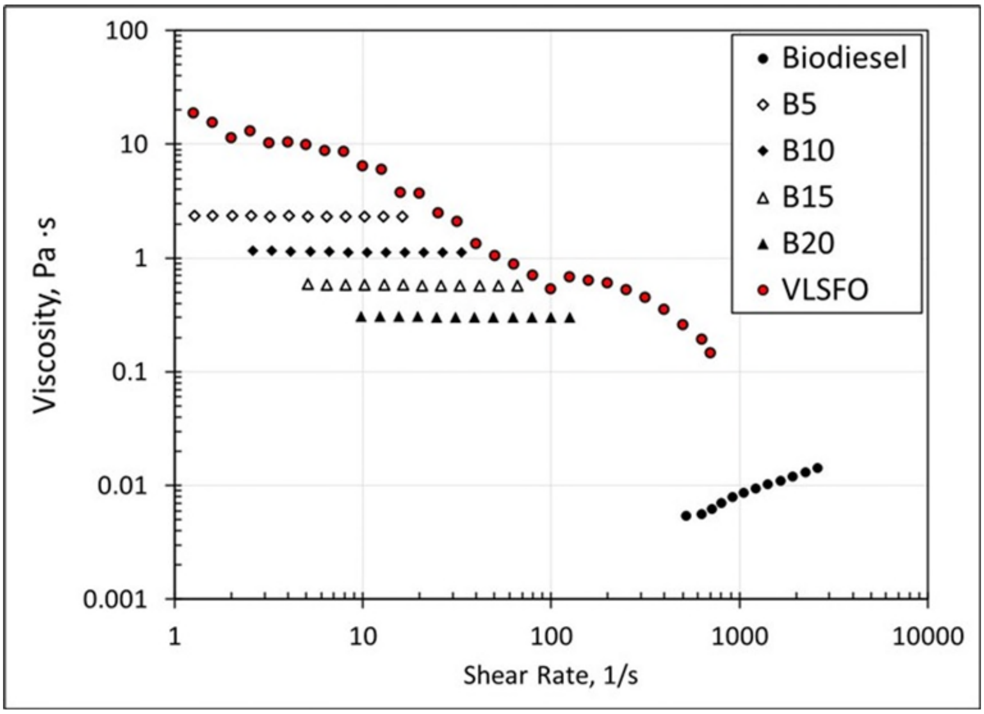



*Figure 48 Dynamic viscosity of VLSFO with biodiesel additions up to 20%.*

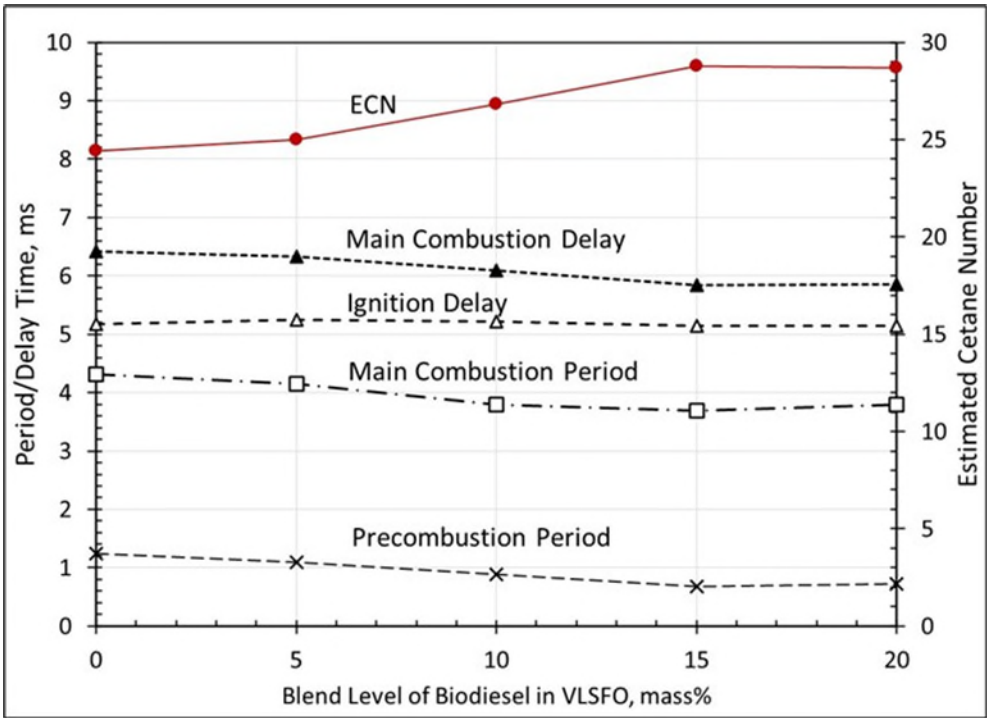



*Figure 49 Estimated cetane number and combustion properties for biodiesel blends with VLSFO.*

## Modeling Support

ORNL has established a digital-twin of a down-scaled, single cylinder, two-stroke crosshead research engine. A model was developed for biodiesel and a surrogate bio-oil based on available literature. A key feature was the development of a reduced chemical kinetic mechanism for simulating bio-oil combustion. *The model was validated against existing data with diesel fuel.* This model retains a large number of chemical species for accurate predictions, including $NO_X$ emissions and the formation of soot precursors. There was excellent agreement between the model and engine performance when operating on ULSD fuel, especially for predicting $NO_X$ emissions.

## Life Cycle Analysis with the GREET Model

Argonne National Laboratory has been conducting life-cycle analysis (LCA) studies to assess the environmental impact of GHG emissions from the marine sector, including biofuels. These studies have included both inland and transoceanic shipping. The fuel chemistries evaluated in this effort are shown in Figure 50. They include petroleum-derived fuels such a heavy fuel oil (HFO), marine distillate oil (MDO), marine gas oil (MGO), liquified natural gas (LNG), methanol (MeOH), Fischer-Tropsch diesels (FTD) and ammonia. Biomass-derived fuels are straight vegetable oil (SVO), bio-oil, FTD, biodiesel (BD), renewable diesel (RD), and biomass derived methanol. Other renewable fuels include e-fuels and biomass-derived ammonia.

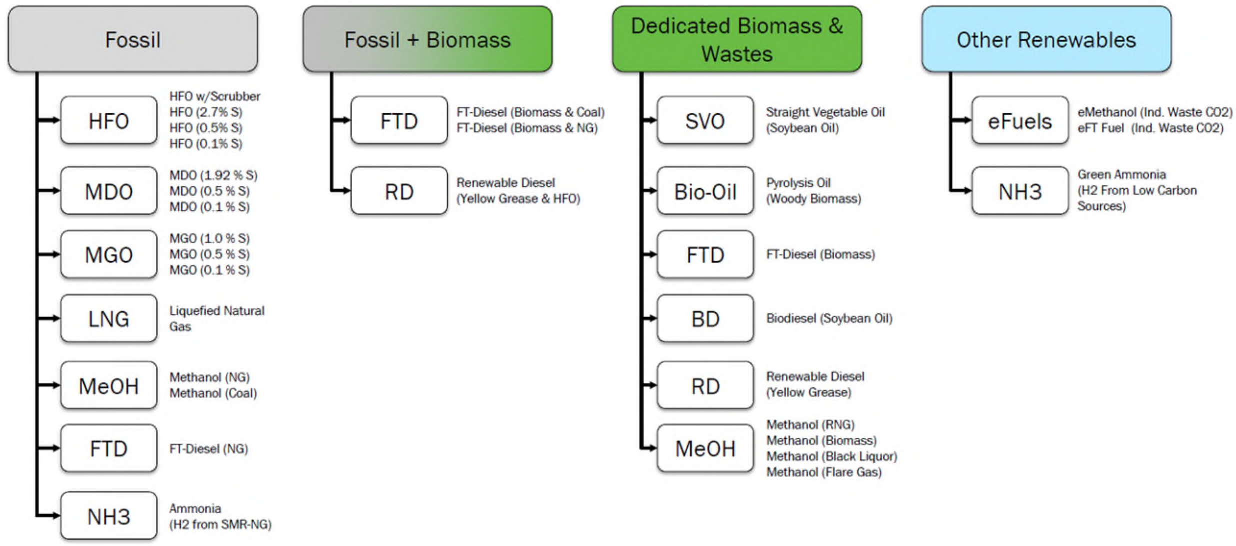



*Figure 50 Listing of fuel categories evaluated in life cycle analysis.*

An example of life cycle GHG and $SO_X$ emissions are shown in Figure 51 along with production pathways. Here it can be seen that significant life cycle GHG reductions can be achieved via biofuels (especially with HTL bio-crudes and bio-oils). Less promising pathways are Fischer-Tropsch fuels derived from biomass and natural gas blending feedstocks. For the estimated reduction of $CO_2$ and $SO_X$ for biofuels, the abatement costs were under \$200/t$CO_2$-eq. This value can be competitive, even when the price of heavy fuel oil is low. In this analysis, biomass-derived fuels outperform those from mixed biomass-fossil feedstocks. When the predicted minimum fuel selling price (MFSP) is plotted against the GHG results (see Figure 52), biomass and waste-based fuels show the best combination of low MFSP and GHG emissions. These are the fuels of most interest in the near term for the marine biofuel feasibility study being conducted at the four DOE national labs.

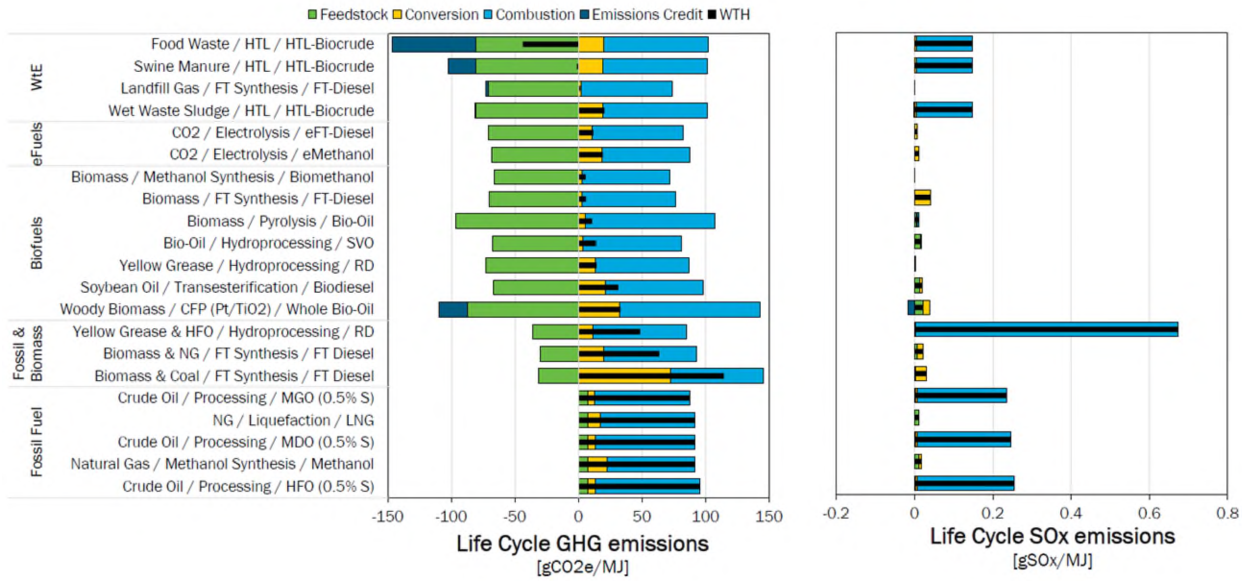



*Figure 51 Life cycle GHG and $SO_X$ estimates for baseline petroleum fuels and biofuels.*

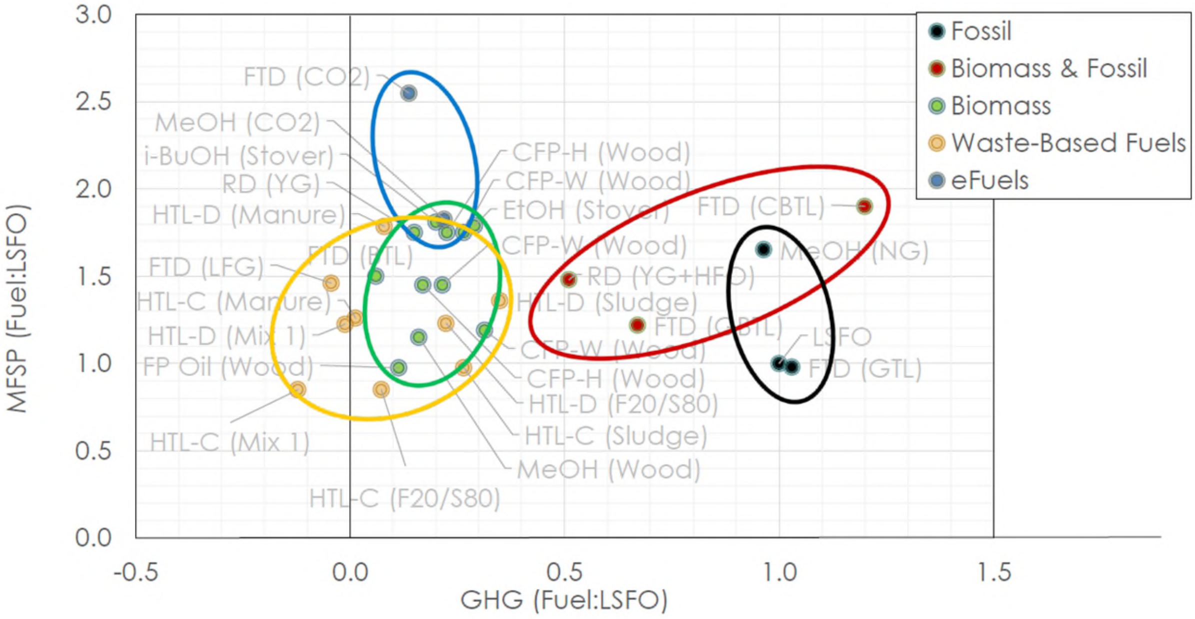



*Figure 52 The estimated MFSP versus GHG emissions for the different fuel chemistries and pathways being considered for fueling the marine sector.*

In summary, regulations are driving the deployment of low-carbon and low-sulfur fuels. Alternative fuels must meet decarbonization targets and the increasingly stringent environmental standards on $SO_X$, $NO_X$, and other environmental pollutant categories. As can be seen, the transition to alternative marine fuels is highly complex, requiring a global outlook and coordination across the value-chain including engine manufacturers, fuel suppliers, ship owners and operators. LCAs are critical for guiding the sustainability of the maritime sector.

## Fuel options for short sea shipping

*The section was written by Trafikverket, Sweden.*

The Swedish Transport Administration has within the international program on Advanced Motor Fuels, Annex 60 – The progress of Advanced Marine Fuels conducted a study on marine fuels for high-speed engines for short sea shipping. The objective of was to describe and compare alternative technologies and fuels applicable for short sea shipping and inland waterway use. Technologies and fuels suitable for road ferries were of special interest.

### Fuels and technologies investigated

The report investigates eight different fuels: hydrogenated vegetable oil (HVO), biogas (compressed (CBG) and liquefied (LBG)), ethanol, methanol, hydrogen, ammonia and shore side electricity including batteries. The aspects covered are maturity, experiences of long term-testing, potential for dual fuel engine application, environmental and health impacts, energy efficiency, risks, cost profile, regulatory framework, manufactural incentives and strategies for the aforementioned fuels and technologies.

### Technology readiness

| | |
|---|---|
| 12 | Established commercial technology |
| 11 | Actual system applied in several different vessel types and applications |
| 10 | Actual system in operation during longer period |
| 9 | Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space) |
| 8 | System complete and qualified |
| 7 | System prototype demonstration in operational environment |
| 6 | Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies) |
| 5 | Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies) |
| 4 | Technology validated in lab |
| 3 | Experimental proof of concept |
| 2 | Technology concept formulated |
| 1 | Basic principles observed |

*Figure 53 Technology readiness*

| Fuel | TRL | Comment – motivation |
|---|---|---|
| HVO | 12 | Can be used in conventional diesel engines without modifications. |
| Methanol | 10 | Two-stroke engines using diesel pilot fuel are available from MAN. They have been installed and are in operation on several vessels, primarily large product tankers intended for methanol transportation. Four-stroke engines approved for marine applications are lacking on the market. Converted dual fuel medium speed four-stroke engines have been operating on the Stena Germanica since 2015 (Ellis & Tanneberger, 2015). The Green Pilot project converted high speed diesel engines to methanol operation (Ramne et al., 2018). The high speed concepts did not use pilot fuel for ignition – one concept used an additive to enhance ignition and the other used spark ignition. Wärtsilä have the technology to produce a four-stroke dual fuel diesel-methanol engine but await the market. ABC Engines in Belgium are developing four-stroke engines for methanol and aim to have an engine on the market during 2022. In 2021 there are in total 25 methanol fuelled vessels in operation and on order (DNV GL, 2021).<br><br>Methanol fuel cell technology is being used on the MS Innogy, a passenger excursion vessel operating in Germany (The Maritime Executive , 2017).There have been fuel cell tests on board a Wallenius car carrier with methanol in the Methapu project in 2006-2009 (Ellis & Tanneberger, 2015). |
| Ethanol | 8 | There are no engines approved for marine applications available from manufacturers. Truck engines using ED95 fuel (95% ethanol with additives) are available. Use of ethanol as marine fuel has not been commercially tested. Ethanol is assumed to work in engines developed for methanol. Ethanol may replace petrol in outboard engines after minor modifications. This has not been verified through long term tests. |
| LBG/CBG | 12 | Marine gas engines are available from several manufacturers. In 2021 there are 204 LNG fuelled vessels in operation and another 294 on order (LNG carriers excluded. Only seagoing vessels are included, inland waterway vessels are excluded) (DNV GL, 2021). |
| Ammonia | 5 | So far, there are no installations on board vessels. Tests using ammonia in a combustion engine have been conducted but the technology is still under development. MAN plans to have a 2-stroke engine available for delivery in 2024 (Motorship, 2021). Wärtsilä has successfully tested an engine running with a fuel mix containing 70 percent ammonia. The company anticipates having an engine concept capable of operating with 100 percent ammonia in 2023 (Wärtsilä, 2021).<br><br>Additionally, there is an ongoing pilot project with a hydrogen fuel cell that is powered by hydrogen created from on-board reformation of ammonia onboard an offshore support vessel. |


| Fuel | TRL | Comment – motivation |
|---|---|---|
| HVO | 12 | Can be used in conventional diesel engines without modifications. |
| Methanol | 10 | Two-stroke engines using diesel pilot fuel are available from MAN. They have been installed and are in operation on several vessels, primarily large product tankers intended for methanol transportation. Four-stroke engines approved for marine applications are lacking on the market. Converted dual fuel medium speed four-stroke engines have been operating on the Stena Germanica since 2015 (Ellis & Tanneberger, 2015). The Green Pilot project converted high speed diesel engines to methanol operation (Ramne et al., 2018). The high speed concepts did not use pilot fuel for ignition – one concept used an additive to enhance ignition and the other used spark ignition. Wärtsilä have the technology to produce a four-stroke dual fuel diesel-methanol engine but await the market. ABC Engines in Belgium are developing four-stroke engines for methanol and aim to have an engine on the market during 2022. In 2021 there are in total 25 methanol fuelled vessels in operation and on order (DNV GL, 2021).<br><br>Methanol fuel cell technology is being used on the MS Innogy, a passenger excursion vessel operating in Germany (The Maritime Executive , 2017).There have been fuel cell tests on board a Wallenius car carrier with methanol in the Methapu project in 2006-2009 (Ellis & Tanneberger, 2015). |
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| | | |
|---|---|---|
| Electricity (batteries) | 12 | Batteries, electric motors and all other required equipment is available from several makers. There are several ships in commission that are powered by batteries. In 2021 there are 331 vessels with batteries. Of these are 47% hybrid vessels, 26 % pure electric and 22% plug-in hybrid (remaining 5% unknown) (DNV GL, 2021). |

*Figure 54 Technology assessment*

## Long term tests

### HVO

HVO is very similar to fossil diesel and can be used as a drop-in fuel in diesel engines. Since 2017 the ferries operated by the Swedish Transport Administration's road ferries on the Hönöleden route have been running some periods on HVO. The change from conventional diesel to HVO did not require any significant modifications or adjustments of the existing engines.

### Methanol

There are currently no marine high-speed engines for methanol on the market and long-term tests are limited to conversions. Since 2015 methanol has been used in converted dual fuel medium speed four-stroke engines onboard the 240-meter long ferry Stena Germanica. The conversion has resulted in reduced $NO_X$- and particle emissions when the engine is operated on methanol fuel. The need for maintenance has also decreased to some extent. Since the start methanol has on average been used in one of the four engines corresponding to 25% of the fuel consumption.

### Ethanol

Currently there are no commercial vessels known to be using ethanol as a fuel. The technology used for methanol is however considered to be adaptable for other alcohols such as ethanol.

### LBG/CBG

LBG/CBG can be utilized interchangeably with LNG/CNG. Any utilization of LNG/CNG can therefore be considered as an example of LBG/CBG use. Today, numerous LNG carriers have long term and good experience with natural gas as a fuel for the propulsion machinery.

### Ammonia

The technology for ammonia is still under development and there are no long-term test results.

### Hydrogen

Hydrogen is relatively new as a marine fuel and has mainly been tested as fuel onboard smaller vessels. Thus there are no results from long term operation.

### Electricity

Electricity has increased rapidly over the last decade and can be considered a proven technology. The main limitations with battery power is range and provision of shore side charging infrastructure. In Norway, there are several road ferries operating on batteries, where E/S Ampere is considered a pioneer vessel.

## Costs

| | Reference Diesel | | HVO | | Methanol | | Ethanol | | LBG/CBG | | Ammonia | | Hydrogen | | Electricity (batteries) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Investment costs (ship) | 0 | Reference | 0 | Same as conventional propulsion, no modifications required | + | Increased investment costs due to additional systems and requirements for low flashpoint fuels | + | Increased investment costs due to additional systems and requirements for low flashpoint fuels | + | Increased investment costs due to additional systems and requirements for low flashpoint fuels and cryogenic storage (probably higher than those for alcohol fuel). | ++ | High investment cost due to high requirements on safety with regard to toxicity and technology development. | ++ | High investment costs due to additional systems and requirements for low flash point fuels and for suitable storage tanks either for compressed or liquified hydrogen. | +(+) | High investment costs for batteries. |
| Current Fuel price [SEK / kWh] | 0,479/ 0,400 | Diesel Mk 1/ Eldningsolja E10 From bunker supplier | 1.30 | Based on actual cost for Färjerederiet | 1.430 | Price estimate from producer of biomethanol (Södra), incl. transport | 1.461 | Price estimate from producer, incl. transport | 0,641 | Based on information from bunker supplier, incl. transport. | *(1.273)* | *Production cost for green ammonia* | 2.7 | Price at filling station for vehicles | About 1.0 | Based on current electricity price in Sweden. |
| Infrastructure | 0 | Reference | 0 | Infrastructure for diesel can be utilized | + | May require intermediate storage tank for bunkering or more frequent truck delivery | + | May require intermediate storage tank for bunkering or more frequent truck delivery | + | May require intermediate storage tank for bunkering or more frequent truck delivery | + | May require intermediate storage tank for bunkering or frequent truck delivery | ++ | May require intermediate storage tank for compressed hydrogen or liquified hydrogen and eventually liquification unit. Alternatively, it would require more frequent truck delivery. | 0/+ | Dependent on grid capacity, may require extension of grid which may be associated with high costs. Additional costs if fast charging is required. |

*Figure 55 Costs for different fuel technologies*

## Effects and impacts

Based on the technology readiness, long-term testing and costs, four fuels and technologies were selected for deeper study of effects and impacts: methanol, LBG/CBG, hydrogen and electricity. For the four fuels and technologies studied, high and low values of GHG emissions were calculated for different fuels in a well-to-wake perspective and compared with conventional diesel (Diesel MK1) and Marine Gasoil (MGO). The results show that the lowest emissions could be reached using electricity and fossil free hydrogen.

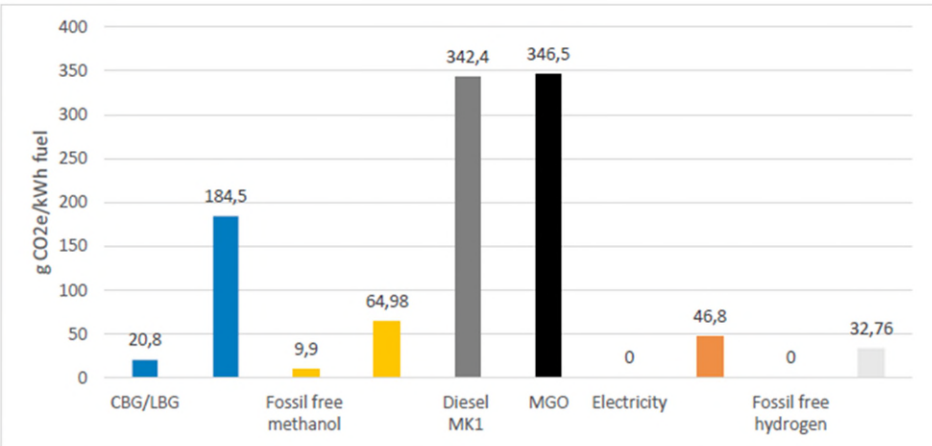



*Figure 3.1 High and low values of GHG emissions (g $CO_{2e}$/kWh fuel) for different fuels in a well-to-wake perspective .*

*Figure 56 High and low values of GHG emissions*

Furthermore, emissions to air were studied and showed no or lower air emission than the use of Diesel or MGO.

*Table 14 Summary of emissions to air and water*

| | Emissions to air | Emissions to water |
|---|---|---|
| Methanol | • Sulphur free – DF diesel engine with fossil pilot fuel - low $SO_x$ – DF diesel with HVO pilot fuel – no $SO_x$<br>• Almost no emissions of PM (due to the absence of carbon-carbon bonds)<br>• Reduction of $NO_x$ compared to diesel: 60-80% (IRENA, 2021).<br>• Size of reduction dependent on type of combustion and temperature.<br>• 2nd generation two-stroke engines using a methanol/water fuel mix fulfil Tier III (Methanex, 2019). | • Soluble in water<br>• Is biodegradable and is not rated as toxic to aquatic organisms (GESAMP, 2014) Not harmful to the marine environment if spilled |
| LBG/CBG | • Sulphur free – DF diesel engine with fossil pilot fuel - low $SO_x$ – DF diesel with HVO pilot fuel – no $SO_x$<br>• Low emissions of PM – especially if using HVO as pilot fuel<br>• Methane slip (amount varies by engine type – see Pavelenko et al. ( 2020)<br>• Reductions of $NO_x$ compared to diesel fuel:<br>• Otto engines fulfils IMO Tier III, diesel engines need exhaust gas aftertreatment system | • Not harmful to the marine environment if spilled |
| Hydrogen | • No emissions when used in fuel cells<br>• No $SO_x$ when used in combustion engines<br>• Low (if using pilot fuel) to no emissions of PM when used in combustion engines<br>• Low $NO_x$ emissions when used in SI combustion engine | • Gas, lighter than air<br>• Not harmful to the marine environment if spilled |
| Shore electricity (batteries) | • No emissions<br>• In the event of a battery fire toxic gas will be released. | N/A |

The energy efficiency was also studied for the different technologies and coupled with fuel efficiency. The fuel cost and energy cost adjusted for technology efficiency was calculated.

*Table 15 Current fuel price range*

| | Diesel MK1 (ref) | Hydrogen | Methanol | LBG/LCG | Electricity from grid |
|---|---|---|---|---|---|
| Efficiency range (ICE - Medium speed engine) | 37%-44% | 28%-44% | 39%-46% | 37%-49% | - |
| Efficiency range (Excluding ICE) | - | 34%-59% | - | - | 86%-95% |
| Relative fuel consumption [9] | 0 (reference) | -25% to +32% | -5% to -4% | -10% to 0% | -57% to -54% |
| Fuel cost [SEK/kWh] (see Table 2.4) | 0.479 | 2.7 | 1.43 | 0.641 | 1.00 |
| Energy cost adjusted for technology efficiency [SEK/kWh] [10] | 0.479 | 1.32 – 3.57 | 1.36 – 1.37 | 0.58-0.64 | 0.43-0.46 |

## Methanol in marine engines

*This section was written by DTI, Denmark.*

Currently, methanol is the most interesting alternative fuel for combustion engines. It can be produced synthetically with simple processes from hydrogen and carbon dioxide, which can be sourced from biological feedstock or combustion processes with carbon capture that makes the process carbon neutral.

Methanol has an octane rating of 110 RON, which makes it more resistant to auto ignition than gasoline. This makes it very challenging to use directly instead of diesel in unmodified diesel engines, as it does not ignite when injected under normal diesel operating conditions. Retrofitting existing 4-stroke engine designs for methanol is therefore not an easy task.

MAN ES has however been successful in developing 2-stroke DF methanol engines based on DF versions for liquid gas, which operate with high pressure direct injection. These engines have been available since 2015.

The most successful implementation in 4-stroke marine engines are also using the dual fuel principle, in which a diesel pilot injection is used to ignite the methanol, which is injected separately.

### 2-stroke engine designs for methanol

Since 2015, MAN ES has offered 2-stroke DF engines that operate with high pressure direct injection of methanol. These engines are available in three versions with the type designation LGIM, as shown in Table 16.

The LGIM designs operate with separate liquid injectors for methanol. Fuel oil injected through standard fuel injectors provides the ignition of the alcohol fuel. The specification for fuel oil consumption is 5 % of the total heating value.

The LGIM engines can operate in IMO Tier II and Tier III mode with methanol. Tier III compliance requires the EGRTC option to be installed. If the engines are operated as intended with methanol as the primary fuel, $SO_2$ removal with scrubbers will not be required for sulfur compliance.

WinGD is developing new DF engines for methanol, which are expected to be ready in 2024.

*Table 16: Specifications for MAN B&W methanol LGIM engines*

| Engine designation | Bore [cm] | Stroke [cm] | Cylinder [number] | Power [MW] | MEP [Bar] | Speed [RPM] |
|---|---|---|---|---|---|---|
| G95 LGIM / EGRTC | 95 | 346 | 6 - 12 | 41 – 82 | 21 | 80 |
| G80 LGIM / EGRTC | 80 | 372 | 6 - 9 | 28 – 42 | 21 | 72 |
| G50 LGIM / EGRTC | 50 | 250 | 6 - 9 | 8.5 – 15 | 21 | 100 |

### 4-stroke engine designs for methanol

Methanol dual fuel 4-stroke engines have recently been approved and released from Wärtsilä, Himsen and ABC.

Wärtsilä and Himsen have developed their engines with high pressure direct injection of methanol in combination with diesel pilot injection. These engines can likely replace more than 90 % of the diesel fuel with methanol from medium to high load using this principle.

ABC engines has chosen a port fueled, premixed combustion concept with diesel pilot injection. The engines can use up to 70 % methanol, based on heating value. The combustion principle has some limitations with regards to the amount of methanol which can be used at high load, as the premixed combustion leads to engine knock which must be avoided.

The Swedish company Scandinaos is offering a range of modified versions of Scania ethanol engines, designed for methanol with ignition improving and lubricating additives. The engine uses direct injection and a high compression ratio to ignite and burn the methanol in the diesel principle. A fuel additive called Beraid is used to improve the ignition.

*Table 17 4-stroke marine engines for methanol.*

| Engine designation | Bore [cm] | Stroke [cm] | Cylinder [number] | Power [MW] | MEP [Bar] | Speed [RPM] |
|---|---|---|---|---|---|---|
| Wärtsilä 32 | 32 | 40 | 6 – 9 | 3.5 - 5.2 | 28.9 | 750 |
| Himsen H32DF-LM | 32 | 40 | 6 – 9 | 3.0 - 4.5 | 24.8 | 750 |
| ABC DZD MeOH | 25.6 | 31 | 8 - 16 | 0.9 - 3.5 | 16.6 | 720 - 1000 |
| Scandinaos MD97 | 13 | 14 | 5-8 | 0.15 - 0.45 | 14.6 | Up to 2300 |

## Emissions from combustion of methanol

Methanol has the potential to reduce both $NO_X$, $SO_2$ and PM. Combustion of alcohols produces only small quantities of PM, and $NO_X$ is lower than with diesel combustion due to lower combustion temperature of alcohols. $SO_2$ is only formed by pilot fuel combustion.

On Stena Germanica, which was the first ship to be powered by methanol, the conversion has resulted in significant reductions in emissions. In methanol operation, $NO_X$ is reduced with 60 %, which moved the ship from Tier I to Tier II compliance (without SCR). $SO_X$ emissions have been reduced with 99 %, PM emissions with 95 % and $CO_2$ emissions with 25 % (Lloyds register, 2015).

### Unregulated emissions from methanol

Experience with smaller methanol powered engines indicates potentially problematic emission levels of aldehydes, unburned methanol, and CO, which are not regulated by IMO Annex VI. Aldehydes are particularly toxic to living organisms including humans, and human exposure should be minimized.

Methanol engines may require oxidation catalysts to keep hydrocarbon and aldehyde emissions low. Sulfur tolerant oxidation catalysts are already available if future regulation is made to limit these emissions.

Methanol can provide a very large reduction in particulate matter, which means that particulate filters may not be considered relevant. If required for any application, such as inland waterways, it will however be uncomplicated to use particulate filters, such as ceramic wall flow filters, which can provide the same reductions in particulate emissions as those used in vehicles today.

## Methanol powered ships

The Swedish ferry Stena Germanica was the first ship to have the engines retrofitted with a direct injection dual fuel injector solution. The ship is equipped with 4-stroke marine engines from Wärtsilä-Sulzer, which were retrofitted between 2014 and 2016. The key components in this setup are the dual fuel injectors developed by Woodward L´orange, which integrate the diesel and methanol fuel delivery in one injector.

A number of conversion projects have also been performed on smaller ships with 4-stroke engines.

In 2021, the Swedish company Scandinaos has developed small methanol powered engines, based on Scania ethanol engines. One of these engines is used in a pilot boat (Pilot 120 SE, MMSI: 265519660) which has been in operation since 2021.

In 2022, The Anglo Belgian Cooperation (ABC) converted two 4-stroke engines on a tug (Methatug) for dual fuel methanol operation. The tug is to operate in the port of Antwerp, alongside other converted vessels such as the Hydrotug, which is converted for hydrogen.

At the end of 2023, a polar research vessel named Uthörn entered operation with 2 x 300 kW diesel engines retrofitted for methanol DF.

Most new ships have been built with 2-stroke methanol engines. From 2015 and October 2023, a total of 23 chemical tankers and a single container ship has been constructed and entered operation with 2-stroke DF methanol engines from MAN.

From 2021 to 2022, Maersk ordered a total of 18 container ships with 18,000 TEU capacity, to be delivered from 2024 to 2026. These ships are to be equipped with MAN G95ME LGIM methanol engines. In 2023, Mærsk ordered 6 more container ships with 9,000 TEU capacity, also fueled by methanol. The Maersk methanol ships are meant to be powered with green methanol, for which the production facilities are now being prepared by multiple actors and production facilities.

In October 2023, a total of 188 ships with methanol DF engines are now on order and are to be delivered within the next 5 years (Figure 57). 150 of these ships will be container ships. The remaining ships are 14 chemical tankers, 7 bulk carriers, 7 offshore vessels and 10 other large ships of various classes.

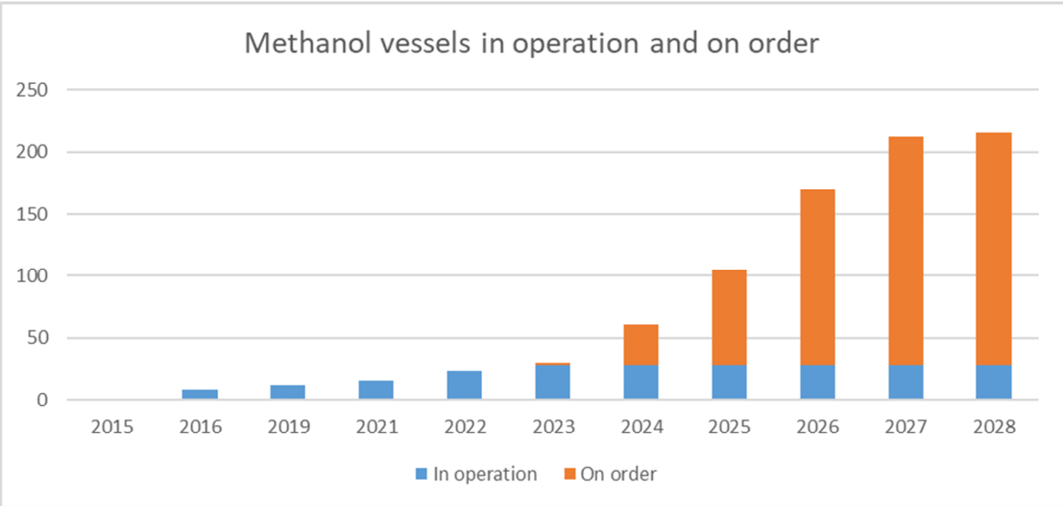



*Figure 57: Development in methanol fueled ships. Source: DNV AFI*

### New 4-stroke design with low compression

Denmark investigated a retrofit solution for larger 4-stroke marine diesel engines to run on methanol without pilot fuel injection.

A 2 MW four stroke engine was successfully converted to run on methanol without pilot fuel injection.

| | | Diesel | Methanol | Reduction |
|---|---|---|---|---|
| NO | ppm | 1200 | 600 | 50% |
| NO2 | ppm | 50 | 20 | 60% |
| NOx | ppm | 1250 | 620 | 50% |
| THC | ppm | 50 | 40 | 20% |
| CO | ppm | 170 | 150 | 12% |
| PM | mg/Nm3 | 25 | 12 | 52% |

*Figure 58 Results* of the 2 MW engine conversion done in Denmark

Three different engine sizes were used to work gradually toward the end goal of 2 MW.

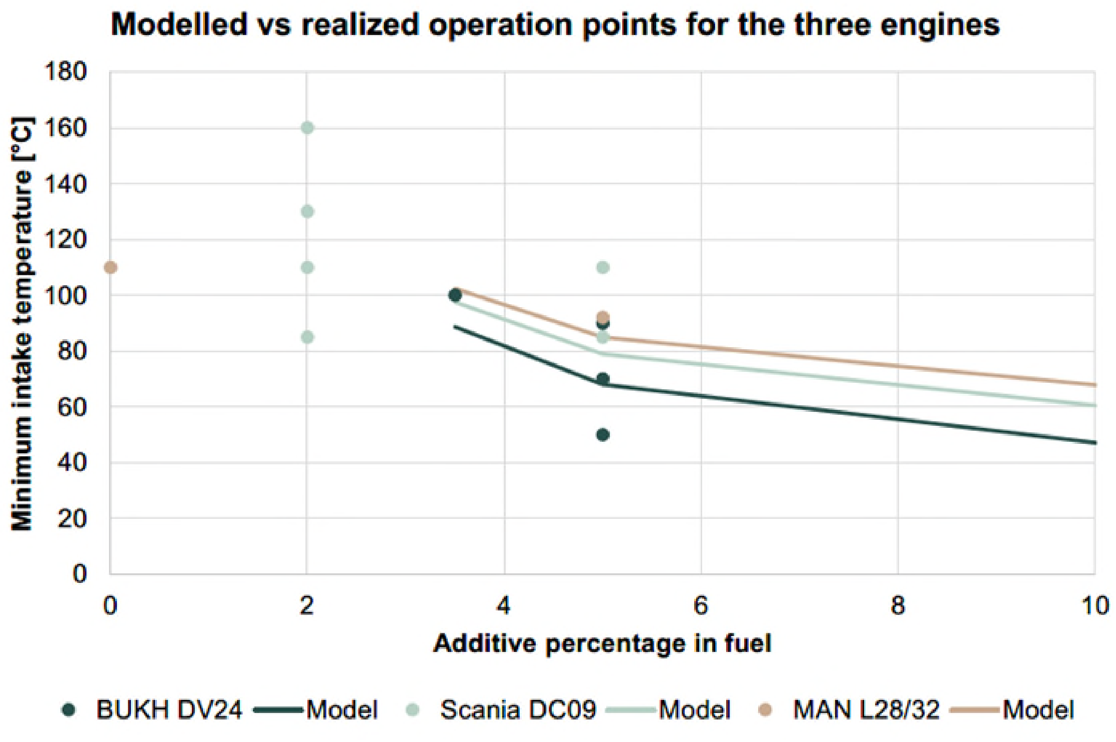



*Figure 59 Test data from experimental methanol engines in Denmark*

# Methanol production, use and safety

*This section was prepared by Päivi Aakko-Saksa, VTT*

## AMF TCP Task 56 report in marine methanol

AMF TCP Task 56 on methanol as fuel for the transport sector reviewed and evaluated different aspects of production of methanol and its use in engines in different transport sectors. Annex III of Task 56 report included the state of the art and research of methanol as fuel in marine application, which was reported by VTT Technical Research Centre of Finland. The reference of the Task 56 report is (Schröder, J., Müller-Langer, F., Aakko-Saksa, P. Winther, K. Baumgarten, W. and Lindgren, M. , 2020)

**Here, Task 56 report, Annex III is presented in a shorter form** in respect of characteristics desired for the marine fuel: Commercial engines available on market, low emissions, compatible with existing infrastructure, available in sufficient volumes, sufficient quality, safe and affordable relative to other advanced fuel options. As a liquid fuel, methanol could serve even overseas marine transport.

## Production

Sustainablility and climate-neutrality of methanol depends on its production. Biomass-based and electro-fuel methanol are routes considered below.

**For biomass based methanol,** from cellulosic feedstocks, several techno-economic studies have been conducted. Hannula and Kurkela (Hannula and Kurkela, 2013) studied 20 individual BTL plant designs with the results showing that FT liquids and synthetic gasoline were more expensive than methanol and DME, whereas FT and MTG are drop-in fuels meaning low system costs. BTL plants studied were attracting at crude oil price of 110-150 $/bbl. (Hannula and Kurkela, 2013). In Sweden, production of methanol from wood biomass, including gasification of wood residual and gasification of pulp mill black liquor, has been tested, e.g. in a pilot plant in Piteå. In Sweden, biomass potential is evaluated to be sufficient to produce enough methanol for the smaller vessel segment. (Ellis *et al.*, 2018).

**For electro-fuel methanol,** production costs have been studied by e.g. Hannula and Reiner and Brynolf et al. (Hannula and Reiner, 2017; Brynolf *et al.*, 2018). The cost of electrolytic renewable hydrogen is dominated by the renewable electricity price. Hannula has estimated that the production costs of e-methane could be 1.5-2.5 times higher than those of hydrogen, while e-methanol would be slightly more costly than e-methane, and e-diesel (Fischer-Tropsch) is the most expensive (appr. 1.4 x e-methane costs). *When considering additional storage and distribution costs, differences in costs between liquid and gaseous fuels narrow*. Whether to use e-hydrogen directly or after conversion to e-fuels is governed by the type of end-use. (Hannula and Reiner, 2017). Production of e-methanol from $CO_2$ is being tested in Sweden from wind energy and $CO_2$ of primarily biogen origin (Liquid Wind ref. in (Ellis *et al.*, 2018)).

**Low-purity methanol** is one possibility to reduce costs of methanol. Today, purity of the 99.85% is specified for the chemical industry, while combustion engines have been shown to operate even when purity of methanol is 90% (ref. in (Ellis *et al.*, 2018)). So far using a lower purity “fuel grade” methanol has been impractical, however, it could be an opportunity for smaller plants producing local renewable methanol for marine sector.

## Methanol infrastructure

Infrastructure for methanol is widely available for shipping purposes, with only minor changes, since methanol is a major commodity produced from natural gas and transported by tankers to different countries and further distributed routinely by road and rail. Distribution of methanol from renewable production plants to smaller vessels can be done by bunkering by tanker truck for conventional fuels. Methanol is routinely transported by tanker truck to customers.

## Methanol engines for ships

*For shipping, dual-fuel marine methanol engines are on market (*Table 18*).* Dual-fuel diesel engines for methanol use in large marine engines have been developed by Wärtsilä and MAN. Wärtsilä has developed a methanol-diesel retrofit concept for four-stroke medium-speed marine engines, called GD methanol-diesel, which has the advantage of using diesel as a back-up fuel (used in the Stena Germanica ferry). In this technology, changes in the cylinder heads, fuel injectors and fuel pumps are needed, as well as a special common rail system and ECU (Haraldson, 2014; Stojcevski, Jay and Vicenzi, 2016). Retrofitting reduces costs, although if the engine is too old it might be more cost effective to replace the complete engine. However, retrofitting has also challenges depending on the generation of the engine to be modified. (Ellis *et al.*, 2018). Another dual-fuel engine concept for methanol developed by MAN for newbuilds is used in several tankers by Waterfront Shipping (Lampert, 2017; Co, 2018)

*Additised alcohol for diesel cycle, MD95 concept, is* commercially available engine heavy-duty engines, namely Scania's engine designed for ethanol with ignition improver and lubricity additive (ED95). This concept has been used since 1985 in over 600 buses supplied by Scania to several countries. The modifications to the diesel engines include increased compression ratio (28:1), a special fuel injection system and a catalyst to control aldehyde emissions.(Hedberg, 2007) This monofuel alcohol engine concept was studied with ethanol ED95 fuels, and preliminarily also with methanol using the commercial additives of ED95, by (Nylund, N.-O. et al., 2015), (Schramm, J., 2016). New research on MD95 concept was conducted in the SUMMETH project (Aakko-Saksa, P. T. et al., 2020).

*Spark-ignited engines,* such as PFI-SI or DI-SI could be used in vessels, with pistons and cylinder heads adapted for spark plugs. These engines are on market for cars, and some smaller size classes for smaller vessels. Some promising advanced combustion systems are under development as described by (Verhelst and Tuner, 2019) and in Appendix 1 of AMF TCP Task 56 report (contribution from Aalto University, Finland). PFI-SI engine is vulnerable to knock.

In principle, methanol engines can have even higher efficiency than diesel engines (Tuner, 2016; Björnestrand, 2017; Shamun et al., 2017), e.g. direct-injection lean operation. Lowest efficiency is expected for concepts running at stoichiometric air-to-fuel ratio, which, however, show ultra-low emissions as three-way catalyst can be used (Tuner, 2016; Björnestrand, 2017).

One issue to consider when developing new methanol engine concepts is the material compatibility due to corrosiveness of methanol. In-cylinder corrosion is to be considered particularly if the engines are used at low loads or frequent start-stop operation without proper warming up of an engine, which is relevant concern for smaller vessels (Ellis *et al.*, 2018).

*Table 18 Comparison of various methanol engine concepts in comparison with HFO/diesel use in marine diesel engines.*

| Engine type | Status | Robust | Power, efficiency | $SO_X$ | HC, CO | $NO_X$ | PM |
|---|---|---|---|---|---|---|---|
| HFO/diesel | Reference | 0 | 0 | 0 | 0 | - | - |
| Dual-fuel | Large ships, on market | - | 0 | + | 0 | + | + |
| MD95 with ox.cat. | ED95 engine on market | - | - | + | 0 | + | + |
| Spark-ignited | See next section “Methanol and other alternatives for smaller ships” (China) | | | | | | |

0 = similar performance with methanol as with HFO/diesel

– = worse performance with methanol than with HFO/diesel

+ = better performance with methanol than with HFO/diesel

## Pollutants and climate emissions

Methanol has low emissions in many respects. Its high oxygen content leads to low carbon based soot emissions in engine combustion, although in dual-fuel engines, diesel pilot may lead to some soot emissions. For MD95, there are no soot emissions, but some unburned additives are seen on particulate filters. Lubricating oil can be also a source of soot emissions.

Dual-Fuel and MD95 concepts can reduce $NO_X$ emission down to approximately 2 g/kWh without SCR system, and even lower $NO_X$ can be achieved by the use of e.g. lean operation or EGR. For current SECA low $SO_X$ emissions with methanol alleviates costs as exhaust aftertreatment with scrubbers are not needed. To secure low HC, CO,aldehyde emissions and organic gases, low-cost oxidizing catalysts can be used. Methanol engines are less noisy than diesel. (Corbett and Winebrake, 2018; Ellis *et al.*, 2018).

*Notable is that impacts of accidental spills of methanol would be less than those of a HFO/diesel spill as methanol is biodegradable.* (Ellis et al., 2018). Thus there are clear environmental benefits for vessels and ships switching to operation on methanol fuels.

In the SUMMETH project, use of methanol as a fuel in smaller vessels showed lower environmental impacts as compared to marine diesel fuels of today. A fuel life cycle comparison showed that methanol produced from renewable feedstock (e.g. wood residuals and pulp mill black liquor) can result in GHG emissions reductions of 75 to 90% (Figure 60). Methanol produced from fossil feedstock results in a slightly higher GHG emission than conventional petroleum fuels. (Ellis *et al.*, 2018). Other evaluations are also available, e.g. by *(Corbett and Winebrake, 2018).*

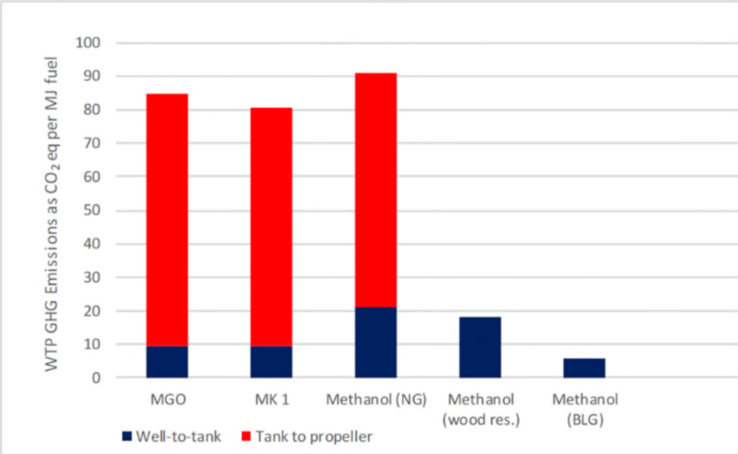



*Figure 60 GHG emissions per MJ fuel for methanol from natural, wood residues, and black liquor gasification (BLG) as compared to marine gasoil and MK 1 diesel. (Ellis et al., 2018).*

## Safety

The large ships using methanol in dual-fuel engines, the Stena Germanica and the Waterfront shipping chemical tankers, have undergone safety assessments prior to approval and to date have been operating safely. International regulations for use of methanol as a ship fuel are under development at the IMO, and classification societies have developed tentative or provisions rules. These international regulations provide guidance for good practice for handling methanol as a marine fuel also in smaller vessels. (Ellis *et al.*, 2018).

For small vessels some requirements applicable for large ships are not suitable, e.g. some automation requirements. However, less special arrangements are necessary for methanol use in smaller vessels than in larger ships. Practically, requirements would be very similar to those for gasoline. (Ellis *et al.*, 2018).

## Research projects

Some examples of the marine methanol projects are as follows:

- MethaShip – renewable methanol a 'long-term solution' for emissions reduction
- LeanShips – Low Energy and Near to Zero Emissions Ships
- SUMMETH – Sustainable Marine Methanol
- UP-TO-ME – Unmanned-Power-to-Methanol-production

There are also activities and research projects on methanol use in fuel cells.

## Methanol and other alternatives for smaller ships

*This section was written by* ESC of MVPA of MIIT*, China.*

### Application Technology of Methanol Fuel for Marine Power

With the rapid development of human society, the contradiction between supply and demand of energy and the deterioration and improvement of living environment is becoming increasingly fierce. As a result, new challenges have been put forward to the traditional energy structure. A series of new energy sources, such as atomic energy, light energy and wind energy, have been developed and utilized to replace the traditional energy forms dominated by coal and oil. Methanol fuel is widely used in the field of transportation due to its advantages of renewable synthesis and low carbon. The International Maritime Organization (IMO) has put forward a grand vision of reducing carbon emissions by 50% in 2050. Methanol fuel is being given high attention in the field of ships. In 2020, The CCC66 meeting of IMO adopted the resolution to use methanol as the main fuel of ships. Wuhan Institute of rules of China Classification Society has completed the preparation of Chinese rules according to IMO resolution.

### Application Technology of Methanol Fuel in Spark Ignition Engines

As the power of automobiles, small gasoline engines have been used in mass production for a hundred years. At present, the annual production and sales volume in the world is about 50million units, with a perfect and high-quality R & D, manufacturing, sales and service system. But the use of gasoline as fuel has brought it into the increasingly fierce contradiction between energy supply and environmental pollution. The above problems can be effectively solved by changing the small gasoline engine to methanol fuel. At present, Methanol Fueled small engines have been used in cars, small SUVs and commercial vehicles, and have been rapidly promoted in Guizhou and other places in China. With the deepening of the research on methanol fuel engine, the fuel efficiency and emission control level are rapidly improving. The relevant test data show that the power rise of methanol fuel engine reaches 30kW.h/L, minimum methanol fuel consumption rate 450g/kW.h. It has reached the economy level of the current gasoline engine. It means that the methanol fuel engine has the ability to partially replace the gasoline engine, and it also makes it possible to effectively use the existing, huge and perfect traditional engine R & D, manufacturing and service system when gasoline and diesel are reduced or restricted. The research and practice of expanding the application range of methanol fuel engine has become realistic and far-reaching significance.

With the government's increasingly strict emission regulations and supervision and management on ship manufacturing and transportation operation, and with the demand for ship power diversification (such as internal combustion drive, electric drive, fuel cell drive, etc.) and low-carbon clean fuel diversification, methanol fuel engine as a marine auxiliary engine is being widely and highly concerned. In China, the development and industrial application of the positive ignition methanol fuel engine as a generator set / extended range power unit has been completed.

Taking the 2000 DWT inland river cargo ship used for inland river ore transportation as an example, the power cell propulsion is selected and the ignition methanol fuel engine is added as the combined power generation range extension system, which can not only realize the electrification of the turbine system of single propeller propulsion / multi propeller propulsion, but also meet the requirements of the emission regulations for ships. Due to the low noise and low vibration of the combined power unit of methanol fuel engine, it can also provide a comfortable operating environment for ship operators. The 1.6L displacement methanol fuel engine is used, M100 methanol is used as fuel, and the electronically controlled sequential inlet injection technical scheme is selected. The rated power is 60kW, and a DC engine with rated power of 40kW is matched, which is defined as a power unit. The power units are combined in parallel to form a power module that meets the needs and form a complete power system with the ship's electric power to meet the shipping needs of 2000 ton inland river cargo ships.

The methanol fuel engine power unit can be composed of N engines, and the intelligent control technology is adopted to comprehensively control and execute the output power, fuel consumption, intake and exhaust system, thermal management system, power output, AC power output, single power start and stop control, vibration and noise reduction control, etc. This constitutes the methanol power unit, which can support the ship electric drive, ship life auxiliary power, ship production and operation power in the form of intelligent power generation output according to the ship application demand.

The power generation unit is composed of positive ignition methanol fuel engine, and the power module is composed of power units. The power module is operated and managed by intelligent control technology, and it is applied to ships to meet the power / power demand of different purposes. Realize the environmental friendliness of ships and reduce the fuel cost of ship operation.

### Diesel/Methanol Binary Combustion Technology

For the marine medium and high-speed main and auxiliary engines, focusing on meeting the emission regulations and the development trend of low sulfur fuel application, the engineering technology team of Tianjin University and Zichai Power Co., Ltd. jointly developed the marine diesel / methanol binary fuel combustion technology. This technical innovation puts forward a new combustion theory, and its combustion mode is between the traditional combustion mode and HCCI (homogeneous charge compression ignition). Its main feature is compression ignition and efficient application of methanol fuel. Based on the molecular structure of methanol fuel, the emission control effect of PM and $NO_X$ in pollutants is particularly significant.

### Characteristics of Diesel / Methanol Binary Fuel Combustion Mode

The combustion process of traditional diesel engine is characterized by "rich premixed combustion" of incomplete combustion products "From the beginning to the end of fuel injection, this kind of rich premixed combustion is an incomplete combustion with poor oxygen, and the combustion enters the PM generation area. Because the combustion process is affected by the fuel injection diffusion rate, the combustion of the mixture is carried out in the process of continuous diffusion and temperature rise, and finally reaches the $NO_X$ generation area, producing a large amount of $NO_X$. Limited by the mixing rate, the combustion heat release of the diesel engine continues until the piston goes down. At the later stage of combustion, the local concentration and temperature bars in the cylinder It determines the emission result, combustion efficiency and thermal efficiency of the engine.

In order to solve the problems of traditional diesel engines, researchers put forward HCCI combustion theory. HCCI combustion mode is considered as an efficient and clean combustion mode. Homogeneous fuel air mixture has been prepared before combustion in the combustion chamber, and the equivalence ratio of the mixture is controlled below the threshold of soot generation. During the compression stroke, the temperature and pressure in the cylinder are rising continuously. The mixed gas reaches the spontaneous combustion condition at multiple points at the same time, so that the combustion occurs at multiple points at the same time, and there is no obvious flame front. The combustion reaction is rapid, and the combustion temperature is low and evenly distributed. Therefore, it has high economy and generates very little $NO_X$ and PM. However, HCCI theory is difficult to be applied in engineering due to its low power density, difficult to control ignition time and serious detonation tendency.

In the diesel / methanol binary fuel combustion mode, methanol is injected into the intake port. Before ignition, methanol has formed a homogeneous mixture with air, and the equivalence ratio of the mixture remains below 1. As methanol is a low active fuel that is difficult to ignite, it is difficult for the piston to ignite by itself when it runs to the top dead center. Therefore, it is necessary to use in cylinder direct injection diesel as the ignition energy source. The mixture of diesel and air ignites first and ignites the surrounding methanol air mixture at the same time. Then, methanol flame propagation and diesel diffusion combustion occur simultaneously in the cylinder. Based on the fact that the premixed combustion contains methanol and more diesel air mixture can be formed during the ignition delay period, the diesel / methanol binary fuel combustion shows a higher premixed combustion peak than pure diesel on the heat release rate curve. Due to the existence of diffusion combustion and flame propagation, the combustion duration of Diesel / methanol binary fuel combustion mode is longer than that of HCCI combustion, but significantly shorter than that of traditional diesel combustion mode. In the diesel / methanol binary fuel combustion mode, the diesel / methanol mixture will not pass through the soot generation zone and may enter the $NO_X$ generation zone when the combustion equivalence ratio of the diesel / methanol mixture remains unchanged and the temperature rises sharply. Due to the addition of methanol, the diffusion combustion quality of diesel fuel is reduced, and the equivalence ratio of diesel air mixture is reduced, which can inhibit the entry into the soot generation area. The mixture of diesel and methanol air realizes multi-point simultaneous combustion in the cylinder, which makes the temperature distribution more uniform, effectively avoids the occurrence of local high temperature zone, and can inhibit the generation of $NO_X$. The combustion process of binary fuel is complex and changeable. The change of combustion process is closely related to engine operating conditions and replacement rate. High substitution rate makes DMDF more inclined to HCCI mode. At low substitution rate, DMDF is more similar to the traditional diesel engine combustion mode. DMDF is obviously easier to control the combustion phase than HCCI.

### Emission Control of Methanol / Diesel Dual Fuel Engine

The emissions to be controlled by marine engines include $SO_X$, $NO_X$, PM/soot, THC/HC and CO.

$SO_X$: methanol does not contain sulfur. The diesel / methanol binary fuel combustion mode can effectively reduce $SO_X$ emissions and realize the effective control of ship power $SO_X$ by replacing diesel with methanol.

$NO_X$ and PM/soot: the diesel / methanol dual fuel combustion mode is efficient and clean, and the engine PM and $NO_X$ are effectively controlled at the same time. With the increase of methanol substitution rate, the effect of reducing PM emission is more obvious.

HC and CO: Although IMO Tier II /Tier III regulations do not require HC and CO of unburned hydrocarbons, Chinese standard gb15097 has specific requirements. The combination of Diesel / methanol binary fuel technology and DOC (Diesel **Ox**idation Catalyst) technology can meet the standard requirements.

## Methanol Fuel Cell

Methanol fuel cell is an electrochemical reaction device that directly converts methanol chemical energy into electrical energy. It has the advantages of primary / secondary battery and internal combustion engine. From the perspective of fuel, methanol is a liquid hydrogen storage medium and a zero carbon energy carrier spanning the oil and gas era (green methanol is prepared from green hydrogen and carbon dioxide). The energy density of methanol fuel is up to 6000wh/kg, the 70MPa high-pressure hydrogen tank is about 1800wh/kg, and the lithium battery is only 200wh/kg. At the same time, methanol storage and transportation are convenient, and the infrastructure covers the eastern coast of China, the eastern coast of the United States, the coast of Europe and some coastal areas in the Middle East; In the world, most coastal cities or sea lanes have the conditions for methanol injection. From the perspective of environmental impact, the $SO_X$, $NO_X$ and PM emissions of methanol fuel cells are nearly zero, the $CO_2$ emission reduction of gray methanol is 40%, and the emission of green methanol is nearly zero; Methanol is biodegradable and difficult to cause long-term impact on the environment. If methanol leaks on a large scale in the water area, it will be diluted rapidly to a low concentration (<1%). Most microorganisms can oxidize methanol into formic acid in enzymatic reaction, and further convert it into carbon dioxide under the action of folic acid. From the perspective of operating cost, the operating cost of methanol fuel cell is only half of that of diesel engine.

At present, methanol fuel cells are gradually accepted as the propulsion power in cruise ships, small passenger and cargo ships / unmanned ships. On October 8, 2021, the first methanol fuel cell powered cruise ship jointly developed by the Dalian Institute of Chemical Physics of the Chinese Academy of Sciences and China Jiahong (Foshan) New Energy Technology Co., Ltd. made its maiden voyage in Xianhu, Foshan, opening a new direction of green shipping. With a length of 15m and a crew of 20, the hybrid system is composed of methanol fuel cells and batteries. Adding 200 kg of methanol can generate about 400 kwh of electricity, and can drive the ship for more than 20 hours at the limited speed of 5.5 knots in the inner lake. To achieve the same driving range, lead-acid batteries need 15-20 tons and lithium batteries need 3-4 tons. Methanol fuel cell powered ships have obvious technical and economic advantages, and will be the first to be popularized and applied in inland rivers. With the improvement of technological maturity, they will play an important role in offshore and ocean transportation in the future.

*Figure 61 "Jiahong 01" methanol fuel cell powered cruise ship*

Methanol fuel cell, as the auxiliary power supply of 1000 ton inland river cargo ship, provides production and living power for ship berthing, berthing, loading and unloading goods, and is undergoing engineering verification. According to statistics, the carbon emission generated by the auxiliary generator during the berthing of ships accounts for 40% to 70% of the total carbon emission of the port, which is an important factor affecting the air quality of the port and its city. As an auxiliary power supply, the efficiency of methanol fuel cell is twice that of diesel engine. It is estimated that compared with diesel generator, the 200 kW auxiliary power supply of methanol fuel cell can save fuel costs of millions RMB per year.

## Online Hydrogen Production by Methanol Water Reforming

The methanol water reforming online hydrogen production device developed and produced by Guangdong Nengchuang Technology Co., Ltd. can be divided into two application lines on fishing boats and cargo ships:

1. It can be combined with hydrogen internal fuel engine as the main force of the ship; Through methanol reforming on-line hydrogen production device, hydrogen with a purity of 70-75% is produced, which is supplied to the hydrogen internal combustion engine for direct combustion. By converting the heat generated by combustion into power to the ship as power, and directly using the exhaust gas of the internal combustion engine to provide reaction heating to the on-line hydrogen production device, the energy efficiency of the whole hydrogen production device can exceed 90%. Because the device uses the exhaust heat energy of the internal fuel engine, the combustion chamber is cancelled, and the whole reaction process has no emission, Pollution free, the production cost of hydrogen rich (hydrogen content 70-75%) is low. 1kg of hydrogen rich can be produced per 5kg of methanol water. According to the current price of methanol (2600 yuan / ton), the cost of hydrogen rich is less than 15 yuan / kg, which has great commercial promotion value.

2. It can be used in combination with hydrogen fuel cells to provide hydrogen with different purity according to different fuel cells. For example, in combination with low-temperature proton exchange membrane fuel cells, methanol reforming online hydrogen production device can produce hydrogen with purity up to 99.97%@co ≤ 0.2ppm, which can be directly supplied to the fuel cell, and then the hydrogen can be converted into electric energy through the fuel cell, which can be supplied to fishing boats and cargo ships for lighting and living auxiliary power. For ships with small power, this device can also be directly used as the main power. In this way, 1kg of hydrogen is produced per 7-7.5kg of methanol. According to the current methanol price and the power consumption during operation, the cost is less than 21 yuan /kg, which has a great cost advantage compared with the price of 60-80 yuan /kg in the hydrogenation station. At the same time, the calorific value of tail gas discharged during hydrogen production can provide hot water to the ship through heat exchange, The heat utilization efficiency of the whole system is improved.

## Comparison between methanol fuel and other fuels used in ship power

The low-carbon transformation of shipping energy is a long-term and complex system engineering. The research and judgment of various clean energy application prospects need to comprehensively consider various factors. In particular, how to break through the dilemma of supply and application, and solve the triangle theory of energy impossibility, that is, it is difficult to give consideration to clean, stable and cheap at the same time. Taking China's water transportation as the research object, this paper compares the low-carbon fuel shipping applications represented by LNG, methanol, biodiesel, hydrogen and ammonia.

*Table 19 Comparison of characteristics of several fuels*

| Parameter | Diesel | Biodiesel | LNG | Methanol | Hydrogen | Ammonia |
|---|---|---|---|---|---|---|
| Molecular Formula | $C_{10}$-$C_{21}$ | R-$COOCH_3$ | $CH_4$ | $CH_3OH$ | $H_2$ | $NH_3$ |
| State | Liquid | Liquid | Gaseous | Liquid | Gaseous | Gaseous |
| Liquid density /$kg \cdot L^{-1}$ | 0.82-0.86 | 0.77-0.79 | 0.42-0.46 | 0.79 | 0.0708 (-253℃) | 0.682 (-33℃) |
| Boiling point /℃ | 180-360 | 180 | -162 | 64.7 | -253 | -33 |
| Flash point /℃ | ＞55 | ＞60 | -188 | 11 | -50 | 11 |
| Spontaneous combustion point /℃ | 250 | 204 | 650 | 465 | 585 | 630 |
| Low calorific value /$MJ \cdot kg^{-1}$ | 42.5 | 44 | 50 | 19.5 | 120 | 18.6 |
| Octane number | 20-30 | | 130 | 111 | 130 | 130 |
| Cetane number | 40-55 | | 低 | 3-5 | - | 0 |
| Flammability limits | 1.58-8.2 | 0.6-7.5 | 5-15 | 6-36.5 | 4-75 | 15-28 |

## Comparison of Application Technology Schemes

Marine natural gas (LNG) engines mainly have two technical routes: high-pressure and low-pressure. The high-pressure model has certain advantages in thermal efficiency, fuel quality adaptability, methane escape control, power range and so on. The low-pressure model performs well in $NO_X$ emission, complexity and cost of gas supply system. In general, the natural gas engine technology is basically mature, and large-scale application has become possible. The industry is carrying out technical research on methane emission control, dynamic characteristic optimization and other aspects.

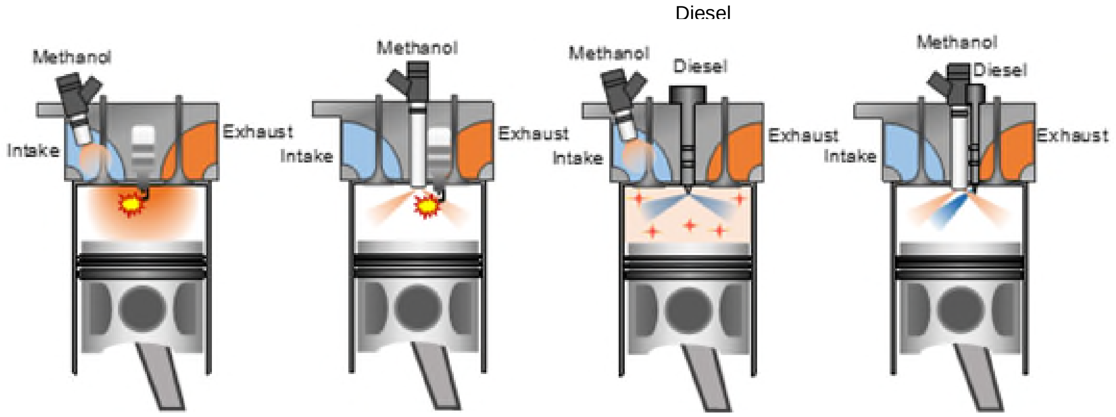
The marine methanol engine is divided into pure methanol engine and methanol diesel dual fuel engine. According to the methanol injection mode, it is divided into cylinder direct injection and airway injection.

a) The methanol premixed ignition PFI-SI (port fuel injection spark ignition) and direct injection spark ignition DI-SI (direct injection spark ignition) positive ignition methanol engine technologies represented by the Swedish green pilot boat project.

b) The methanol dual fuel engine technology of methanol / diesel cylinder high pressure direct injection HPDF (high pressure dual fuel) represented by German Mann and Wartsila, Finland, can operate in both dual fuel mode and diesel mode (D mode).

c) China Zichai Power Co., Ltd. cooperates with the State Key Laboratory of internal combustion engine of Tianjin University to develop marine methanol / diesel dual fuel engine technology. Methanol / diesel dual fuel DMDF (diesel methanol dual fuel), methanol is injected in the intake pipe, methanol and air form a homogeneous mixture, which is ignited by diesel in the cylinder. This method has small changes to the prototype, good inheritance, high thermal efficiency, stable low load operation, and can operate in pure diesel mode (D mode) under special circumstances, especially suitable for medium and high-speed engines of inland and offshore fishing vessels and cargo ships.

*Figure 62 Methanol combustion concepts*




(a) PFI-SI Methanol premixed ignition | (b) DI-SI Methanol direct injection ignition | (c) DMDF Binary fuel combustion | (d) HPDF Double jet ignition

Biodiesel is a kind of biomass energy, which contains 77% carbon, 12% hydrogen and 11% oxygen, as well as trace sulfur and nitrogen. The main combustion component is fatty acid methyl ester. Biodiesel can be made from oil crops, aquatic plants, animal fats, waste cooking oil, etc. The research shows that the performance of biodiesel is close to that of petrochemical diesel. The industry has carried out a series of on-board tests around the application of fatty acid methyl ester (FAME) and hydrogenated vegetable oil fuel (HVO). Fame can only be mixed with diesel in internal combustion engines at present, and the mixing proportion should not exceed 7%. HVO is similar to MgO in composition and physical and chemical properties and can be directly used in internal combustion engines without modification.

Hydrogen diesel dual fuel internal combustion engine has been studied on small passenger ships. Hydrogen diesel dual fuel medium speed engine is currently in the research and development stage, and the industry is targeting hydrogen fuel high-pressure injection; Increase ignition energy; For possible detonation caused by fast flame propagation; The combustion temperature is too high; Carry out key basic research and engineering application key technology research on a series of issues such as $NO_X$ emission control.

The research and development of ammonia fueled internal combustion engine is in progress, focusing on a series of problems such as high spontaneous combustion temperature, slow flame propagation speed, narrow flammability limit range, high gasification latent heat, emission control (especially N2O) and conversion device stability. In terms of ammonia fuel engine technology, a scientific research team has carried out research on a variety of combined combustion technologies, such as airway low-pressure injection, cylinder high-pressure injection, precombustion chamber ignition, cylinder diesel ignition, etc.

### *Comparison of Exhaust Pollutants*

Conventional emissions from traditional diesel engines： PM, $SO_X$, $NO_X$, HC, CO, etc.

The pollutants of low sulfur MGO diesel are mainly PM and $NO_X$, and $NO_X$ in the emission control area (ECA) needs to be controlled by SCR device.

The emission pollutants of heavy oil are mainly PM, $SO_X$ and $NO_X$, and the emission is higher than that of MgO diesel. The control mode is mainly scrubber and SCR.

As a marine power fuel, methanol is easy to comply with PM and $NO_X$ in exhaust pollutants. There are relatively many HC and CO in premixed methanol engine, so doc device can be selected for removal. The content of various pollutants emitted by direct injection methanol engine can be well controlled.

Hydrogen and ammonia are used as marine power fuels, because they do not contain carbon, so the generation of PM is very low, and HC and co will not be produced, but $NO_X$ will be produced, which must be controlled by SCR technology.

## Exhaust Greenhouse Gas Comparison

There are at least seven kinds of greenhouse gases (GHG), including carbon dioxide ($CO_2$), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCS), perfluorocarbons (PFCs), sulfur hexafluoride (SF6), and nitrogen trifluoride (NF3). The harmful substances related to the impact of ship power on greenhouse gas emissions are mainly the first three emission products.

The contribution of carbon element in LNG to carbon dioxide emission reduction is limited, and methane escape during use will have a certain impact on greenhouse gas emissions.

As a marine fuel, biodiesel has the same $CO_2$ emissions as diesel. Because the carbon element comes from renewable biomass, it can be considered as a fuel to achieve "carbon neutrality".

Methanol is prepared from hydrocarbon energy. At present, 70% of China's methanol production capacity is coal, and the international raw material for methanol preparation is mainly natural gas. In 2020, after China put forward the goals of "carbon peaking" and "carbon neutralization", in view of the development requirements of the promotion and application of clean energy, it proposed to use renewable energy to produce hydrogen and capture carbon dioxide to synthesize methanol, so as to realize the comprehensive utilization of carbon dioxide resources. This work is being carried out in an all-round way and is expected to produce more than 20million tons of renewable energy methanol by 2030.

The exhaust emissions of hydrogen fueled engine applications do not contain greenhouse gases.

The application of ammonia fuel engine will not produce $CO_2$, but the exhaust emissions will produce $N_2O$ in greenhouse gases.

## Fuel Safety Comparison

LNG is a non-toxic and non corrosive gas fuel. The internal space of the ship, especially the engine room, has various and complex equipment, so open flames and sparks should be avoided. The marine LNG system has been basically mature, generally including filling system, LNG fuel tank, evaporator, gas valve unit (GVU), double wall pipe and inert gas system. All existing LNG power ships use C-type fuel tanks. There are many openings below the liquid level of LNG fuel tank, and the leakage must be strictly controlled. The liquefied gas in the fuel tank needs to be gasified, heated and pressurized before entering the dual fuel engine for combustion.

Methanol protection requirements. Methanol is corrosive to some rubber materials and aluminum alloy materials. Special attention should be paid to the selection of sealing materials in the methanol fuel transmission and distribution system and methanol fuel engine.

Ballast tanks and double bottoms are allowed for the storage of methanol on board, and the fuel tanks under the water surface may not be equipped with isolation tanks.

The main problem of biodiesel as a marine power fuel is that it will undergo oxidative degradation over time. The degradation products are insoluble resins, organic acids and aldehydes, which will lead to the failure of internal combustion engines and injectors.

As a marine power fuel, the core problems of hydrogen are hydrogen carrying, sealing of connection system, escape control, safety monitoring, etc.

As a marine power fuel, the core issues of ammonia are the system control, stability, consistency and reliability of the conversion device from liquid to gas, the monitoring of ammonia escape and the rapid purging disposal. In particular, prevent ammonia leakage from damaging the water ecological environment.

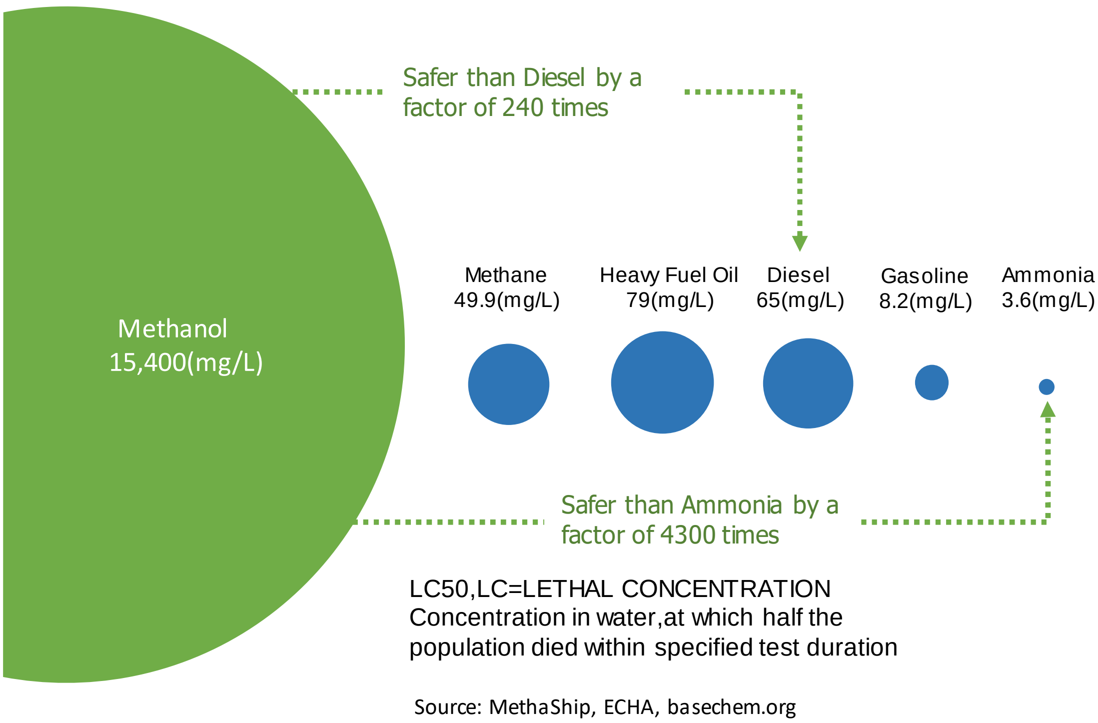



*Figure 63 Toxicity of marine fuels*

## Comparison of Fuel Reserves for Building New Ships

Energy density, especially volume energy density, is one of the key indicators to assess the feasibility of different clean energy applications on board. It determines the space required for loading fuel on board and affects the cargo carrying capacity of the ship. The higher the volume energy density, the longer the endurance mileage can be obtained with the same fuel tank volume. Fishing vessels are divided into offshore fishing and ocean fishing. The materials for preparation of offshore fishing vessels have clear requirements for fuel storage. Ocean fishing and ocean ships have high requirements for endurance and are sensitive to the volume energy density index of fuel; Offshore ships and inland river ships have relatively low endurance requirements and low sensitivity to volume energy density.

According to the data in Table 7, the theoretical equivalent calorific value is replaced by 1m $^3$ Volume of diesel, 1.04 m $^3$required biodiesel, 1.62 m $^3$ Liquefied natural gas, 2.32 m $^3$ methanol, 4.20 m$^3$ liquid hydrogen, 2.81 m$^3$ liquid ammonia, among which liquefied natural gas, liquid hydrogen and liquid ammonia tanks need thermal insulation materials, necessary safety space, and more safety auxiliary equipment, so the actual occupied space will be larger.

Biodiesel, the endurance capacity of the oil tank with the same capacity is consistent with that of the diesel system.

Methanol fuel can be stored in the original diesel fuel tank or in the ship's ballast tank. The methanol fuel tank under the water surface may not be equipped with an isolation tank, and it is allowed to use a double bottom space to store methanol.

There is no specification for the storage of hydrogen in marine fuel, and there is no hydrogen powered ship. The industry mainly uses high-pressure gas cylinders to store and transport hydrogen. The sealing and leakage problems still need to be paid close attention to in this storage and transportation mode.

The boiling point of ammonia fuel is -33 °C which is stored in liquid form under 7-8 atmospheric pressures and converted into gaseous fuel. The energy density of ammonia is lower than that of diesel oil, so the ship needs to design a larger space for storing ammonia fuel, which is used to arrange the space for ammonia fuel storage, safety protection and liquid gas conversion devices.

### Comparison of Transformation Possibilities of Ships in Use

## Engine modification:

As a fuel, biodiesel does not require technical transformation of the engine.

Methanol fuel engine technology is mature, and IMO standards and regulations have been issued and implemented.

LNG fuel engine technology is mature, the system is complex, and the standard specifications have been issued and implemented.

Ammonia fueled engines need fuel storage, safety protection and liquid gas conversion devices, and are currently in the stage of engineering research.

Hydrogen fueled engine needs complex fuel storage hydrogen and fuel supply system, which is currently in the stage of engineering research.

According to the difficulty of engine technical transformation, the low-carbon clean fuel used in the transformation of ship power is biodiesel, methanol, LNG, ammonia and hydrogen from low to high.

## Hull modification:

The hull reconstruction is mainly composed of fuel storage and supporting fuel pretreatment system. According to the reconstruction difficulty, the order from low to high is biodiesel, methanol, LNG, ammonia and hydrogen.

*Table 20 Comparison Table of Low Carbon Clean Fuel Reserves for Ships in Use*

| | Use the original fuel tank | Add fuel tank | Add special storage tank |
|---|---|---|---|
| LNG | | | √ |
| Methanol | √ | √ | |
| Biodiesel | √ | | |
| Hydrogen | | | √ |
| Ammonia | | | √ |

Note: The selection of liquid fuel at normal temperature and pressure is the lowest cost scheme for ship transformation.

For the application of low-carbon clean fuel in ship power, in addition to the above technical scheme and convenience, the total amount of fuel, transportation and distribution guarantee, supply and other factors should also be considered.

Based on the data obtained in this research report, the application of low-carbon clean fuels in ship power, whether in ship reconstruction or new ship manufacturing, should be the first choice according to the two dimensions of total fuel volume and supply, which can achieve "carbon neutrality" and sustainable development. As the mainstream fuel of future ship power, methanol has won the consensus of the industry.

### Methanol Fuel Filling for Ship Power

In view of the properties of methanol fuel as a liquid at normal temperature and pressure, the filling of methanol fuel for ship power can be carried out in full accordance with the current liquid fuel filling specifications.

#### Refueling on River and Sea Surface

According to the requirements of national maritime regulations, the power fuel filling of river and sea surface ships is divided into two filling modes: service area barge filling and mobile filling.

Fill with mobile filling ship. The fuel filling ships on the river and sea surface determine the tonnage plan of fuel to be filled and the coordinates of berthing anchorage through telecommunication inquiry. The fuel filling service area applies for a maritime operation permit 24 hours in advance. After obtaining the maritime administrative permit, the dangerous goods mobile refueling ships are arranged to carry the fuel to the predetermined coordinate anchorage, and after the professional companies (approved and designated by the maritime department) take leakage prevention measures, The filling operation shall be carried out by the staff of the mobile filling ship according to the standard process of dangerous goods handover.

Fill barges in the service area. The mode of fuel filling on the river and sea surface is that the ships inquire and make an appointment in advance through telecommunication. The lighter in the fuel filling service area (the maritime department designates the location and implements the whole process supervision), according to the tonnage of the ship filling fuel and the planned fuel filling volume, prearranges the reserved parking position, and the lighter staff carries out the fuel filling operation according to the standard process of dangerous goods handover.

### Port Filling

At present, the maritime department has not issued the specifications and permits for the implementation of ship power fuel filling at the port terminals. There are corresponding regulations and requirements for the loading and unloading of cargo fuel at dangerous chemical terminals, but they are not applicable to ship power fuel filling.

At present, in the process of developing the application of methanol fuel for ship power, China's shipbuilding industry has specially developed a methanol fuel skid mounted station at the wharf to provide fuel filling for the methanol fuel ships developed. The work of exploring a new mode of marine power fuel filling is under way.

### Marine Power Methanol Fuel Filling Equipment

Methanol fuel mobile refueling ship has the characteristics of flexibility, speed and convenience. In inland river and coastal surface transportation and operation areas, including offshore fishing grounds, the fuel supply of fishing vessels is considered to be the preferred way of methanol fuel injection.

Methanol fuel mobile refueling ship: Based on the chemical characteristics of dangerous goods of methanol fuel, the applicable ship is a dangerous goods chemical ship. It is suggested that the construction of new dangerous chemicals ships should be built according to the marine ship manufacturing standards (stainless steel is recommended for hull construction), so as to realize the river sea combined transportation mode as soon as possible.

Requirements for the construction tonnage of methanol fuel mobile refueling ship: considering the fuel economy of the daily sailing mileage of methanol fuel refueling ship and the convenience of refueling operation. The newly built ships should be 300 tonnage and 3000 tonnage, so as to meet the needs of retail and wholesale business.

Methanol fuel filling equipment: it shall have the unloading gas phase recovery system and fuel filling gas phase recovery system. Compared with traditional diesel filling equipment, the anti-corrosion function needs to be strengthened. Avoid using metal materials such as aluminum alloy and zinc alloy. Equipped with safety and emergency protective equipment such as goggles, eye washers, corrosion-resistant gloves, etc.

The setting of daily berths for methanol fuel mobile refueling ships: generally, there are three berthing modes: port dock berths, water service area ship berths, and dangerous goods ship anchorages.

Methanol fuel supply for mobile refueling ships: receive methanol fuel in the port methanol fuel refueling warehouse or the water service area reservoir area and implement fuel refueling with the administrative permission of the maritime department according to the service contract and plan arrangement. In the methanol fuel filling operation, ensure that there are professional personnel to carry out the preparatory work of anti-leakage and pollution measures.

## Supply And Guarantee of Methanol Fuel for Ships

Methanol fuel filling water service area: the construction project party shall provide chemical barges that meet the relevant regulations of the classification society, meet the fire protection, environmental protection, safety supervision, navigation evaluation and acceptance, and anchor and fix them on the anchorage approved by the maritime department.

The setting of fixed anchorage in the water service area: it is recommended to meet the local official regulations, the infrastructure construction should meet the official safety supervision requirements, and the selection of anchorage should be based on demand and convenient services.

Special tips: to achieve environmental friendliness and meet the trend of promoting the application of low-carbon clean fuels, the construction of water service areas should have tap water supply, oil and sewage reception, shore power connection and other facilities.

The main functions of the water service area: it can meet the methanol fuel filling of ships, and provide the crew with supplies of daily necessities, crew annual inspection, Port declaration, maritime administrative declaration, regulations publicity, etc.

Methanol Fueled dangerous chemical vessels in the water service area should have the following safety precautions in their daily production operations.

(1) Emergency disposal measures for ships touching nearby hydraulic facilities

(2) Emergency measures for personnel falling into water

(3) Emergency measures for fire and explosion accidents

(4) Emergency measures for ship collision accidents

(5) Emergency measures for ship grounding accident

(6) Emergency measures for ship out of control

(7) Emergency measures for ships in danger of sinking

(8) Emergency measures for oil spill accident

(9) Emergency disposal measures for ships in bad weather

After the above emergency plan is prepared, it shall be reported to the competent maritime authority for filing.

## Volatilization Control And Supervision of Fuel Storage And Filling

Methanol fuel filling and storage should be equipped with the determination, monitoring and disposal of the leakage index concentration at the closed point of the oil and gas recovery system, the monitoring of the emission concentration of the oil and gas treatment device, and the determination of the excessive emission concentration of the oil and gas treatment device in the oil depot.

China has standard regulations on fuel storage, transportation and filling. The Ministry of Ecological Environment and the State Administration of Market Supervision jointly issued <The Emission Standard of Air Pollutants for Oil Storage (GB 20950-2020)>, <The Emission Standard of Air Pollutants for Oil Transportation (GB 20951-2020) >and <The Emission Standard of Air Pollutants for Gas Stations (GB 20952-2020)>. At present, the road transportation field is implemented according to the above standards. Ship fuel shall also be subject to the above standards.

## Progress Assessment Summary

### Comparison of Technical Solutions

#### *Methanol Technical Solutions*

*Table 21 Technical Scheme of Methanol Application in Marine Engine*

| Item / Scheme | Applicable Engine Type | Technology | Maturity | Application Examples | Note |
|---|---|---|---|---|---|
| **Spark Ignition Engine** | medium and high speed engine | Spark plug ignition | Mature | Spark ignition methanol engine modified with natural gas. (trial operation in Sweden) | The existing diesel engine needs to be replaced. Applicable to new ship construction |
| **Compression Ignition Engine** | medium and high speed engine | Diesel / methanol binary combustion technology | Mature | Jianglong boat loading, Zichai bench test, Nantong fishing boat test operation | Both new ship manufacturing and in-service ship transformation can be used |

#### *LNG Technical Solution*

*Table 22 Technical Scheme of LNG Application in Marine Engine*

| Item / Scheme | Applicable Engine Type | Technology | Maturity | Application Examples | Note |
|---|---|---|---|---|---|
| **Spark Ignition Engine** | medium and high speed engine | Spark plug ignition | Mature | Weichai Zichai | The existing diesel engine needs to be replaced. New ships are more applicable |
| | medium and low speed engine | Spark plug ignition | Appliable | Yuchai Zichai | Both new ship manufacturing and in-service ship reconstruction can be used |
| **Spark Ignition Engine** | high speed engine | Diesel/LNG double fuel | Testing | Some ships in the Yangtze River Basin | The existing diesel engine needs to be replaced. New ships are more applicable |
| | Medium, high and low speed engine | Diesel/LNG double fuel | Partial application | Some ships in the Yangtze River Basin | Both new ship manufacturing and in-service ship reconstruction can be used |

#### *Power Battery Technical Solution*

*Table 23 Technical scheme of marine engine power battery*

| Item / Scheme | Applicable Engine Type | Technology | Maturity | Application Examples | Note |
|---|---|---|---|---|---|
| **Replace the existing engine with electric motor drive** | medium and high speed engine | Electric drive | Testing | Ferries and tourist boats in some areas | The existing diesel engine needs to be replaced. The new ship is more applicable |

## *Methanol Fuel Cell Technical Solution*

*Table 24 Technical scheme of fuel cell for marine engine*

| Item / Scheme | Applicable Engine Type | Technology | Maturity | Application Examples | Note |
|---|---|---|---|---|---|
| **Replace existing engine** | high speed engine | Fuel cell (hydrogen and methanol as fuel) | testing | testing | The existing diesel engine needs to be replaced. The new ship is more applicable |

## Comparison of Fuel Application

*Table 25 Comparison of alternative fuel applications for ships in China*

| Comparison of main contents of alternative fuel application schemes for ship power in use | | | | | |
|---|---|---|---|---|---|
| Fuel | LNG | Diesel/Natural gas | Methanol | Diesel/Methanol | Power battery / Lead-acid battery |
| Power type | Spark ignition | Compression ignition engine | Spark ignition | Compression ignition type (diesel start, diesel / methanol dual fuel operation) | Power battery pack + electric propulsion unit |
| Scheme | Transform the existing engine intake system and fuel system, Adding LNG fuel injection and supply control system | | Retrofit the existing engine intake system and fuel system, Install methanol fuel injection control and supply system | | Replace battery pack + electric propulsion unit |
| Emission | Meet the requirements of national standards If lean burn technology is adopted, NOx emission is high It is necessary to adopt post-treatment technology and install post-treatment devices. | | Low soot and nitrogen oxide. It only needs to install simple post-treatment, and the cost is 35% lower than that of pure diesel | Low soot and nitrogen oxide. It only needs to install simple post-treatment, and the cost is 35% lower than that of pure diesel | Zero |
| Permission | National license | | It has passed the MSC of the international maritime organization 1622 fuel regulations | | Lead acid batteries are licensed by the state. Except that lithium iron phosphate batteries can be used in ships, the safety of other types of lithium batteries is controversial |
| Policy Permission | Some local governments have policies | | Licensing policy is under development | Licensing policy is under development | Lead acid batteries are licensed by the state. Except that lithium iron phosphate battery has obtained CCS certification, other types of lithium batteries have not been certified by CCS |
| Transformation Cost | High (some natural gas injection devices need to be imported) | High (some natural gas injection devices need to be imported) | low (about 30% of the reconstruction cost of LNG) | | high (the cost of lead-acid battery is lower than that of lithium battery), and electric propulsion devices need to be added. |
| Running Cost | It is slightly lower than diesel in summer and higher than diesel in winter | It is slightly lower than diesel in summer and higher than diesel in winter | low (the fuel cost is more than 15% less than that of diesel) | | low (long charging time and short driving range) |
| Maintenance cost | high (maintenance of double wall pipe is difficult, special engine oil is required) | | low (same as diesel engine. No special lubricating oil required) | | high (replace the battery pack is high) |
| Disassembly cost | Same as ordinary diesel engine | | Same as ordinary diesel engine | | low (mechanical parts are greatly reduced) |
| Note | Replace the engine. The fuel tank needs to be placed on the deck, and the hull structure needs to be redesigned and matched. The fuel intake pipe must be of double wall structure. Add relevant safety monitoring system. | | Replace the engine . The fuel tank is the same as the diesel tank of the original ship. | Do not replace the engine during the transformation of the ship The fuel tank is the same as the diesel tank of the original ship. | If as the propulsion system, it needs to be redesigned as a whole. Carbon emission indicators, based on China's current energy consumption structure of power production, the carbon emission indicators of batteries are equivalent to diesel. If battery recycling and pollution-free treatment are considered, the carbon emission index of battery is higher than that of diesel. |

## Fuel Supply and Support Comparison

*Table 26 Comparison of alternative fuel infrastructure*

| Comparison of main contents of supply and support of different alternative fuels for ship power | | | |
|---|---|---|---|
| **Content** | **LNG** | **Power Battery** | **Methanol** |
| Fuel filling convenience | difficult | medium | easy |
| Fuel carrying payload space | medium | small | big |
| Fuelling infrastructure | By November 2020, 21 shore based LNG filling stations have been built nationwide, and 4 have been put into use. | / | Under construction |
| Shore based pipeline filling and infrastructure | Large investment, many infrastructure links<br>High safety requirements | / | Easy to operate, convenient to fill, and easy to obtain at ports or supply centers |
| Shore based tank car filling and device | High complexity, unsuitable for operation | / | Easy to operate |
| Barge filling | Complex safety process | / | Easy to operate |
| Mobile refueling vessel | Complex safety process | / | Easy to operate |
| Shore charging device | / | Large limitations, many supporting links, large infrastructure investment and difficult operation | / |
| Safety specifications | High | High | Low |
| Access permit | High | High | Low |

## Adaptability Comparison

*Table 27 Comparison of alternative fuel applicability for Chinese ships*

| Comparison of regional adaptability of alternative fuels for different ship types | | | |
|---|---|---|---|
| Content | LNG | Power Battery | Methanol |
| Inland water transport | LNG filling station support is required | Applicable to ferry | Applicable |
| River-sea transportation | LNG filling station support is required | Not applicable | Applicable |
| Offshore transportation | LNG filling station support is required | Not applicable | Applicable |
| Offshore fishing vessel | LNG filling station support is required | Not applicable | Applicable |
| Water surface operation | Only applicable to fixed operation engineering ships | Not applicable | Applicable |
| Bulk carrier | LNG filling station support is required | Applicable to small ships | Applicable |
| Ro-Ro ship | LNG filling station support is required | Not applicable | Applicable |
| Ferry | LNG filling station support is required | Applicable for short distance | Applicable |
| Cruise Ship | LNG filling station support is required | Applicable for small sightseeing boats | Applicable |
| Pilot Vessel | LNG filling station support is required | Applicable for short distance | Applicable |
| Craft | LNG filling station support is required | Not applicable | Applicable |

## Suggestions and Prospects

### *Suggestions on The Application of Methanol Fuel in The Field of Ships*

(1) In view of the environmental friendliness of methanol fuel to inland water resources and marine water resources, the promotion of methanol fuel application by fishing vessels can not only protect water resources, but also effectively reduce pollution to the storage, transportation, and storage of fishing biological products. Suggestion: the regulation and management of mobile fuel supply for fishing vessels operating in exclusive fishing grounds and fishing periods need to be explored and studied.

(2) Inland navigation and surface operation equipment ships, because their navigation and operation are in the fresh water system, it is particularly important to prevent ships from polluting water resources. In view of the friendly characteristics of methanol as a low-carbon clean fuel and pollution to water resources, it is suggested that the global shipping industry and government departments and institutions around the world should issue corresponding policies from the perspective of policies, regulations and incentive mechanisms. Encourage inland river shipping, offshore transportation, river sea direct transportation and tourist passenger ships to promote the application of methanol fuel.

(3) At present, there are two ways of bunkering ships approved by the Chinese government: choose the lighter in the bunkering service area to carry out bunkering, choose the anchorage of the ship, and use the mobile bunkering ship to carry out bunkering according to the standard process of dangerous goods handover. With the application and popularization of methanol fuel, it is convenient to provide fuel filling for ships berthing at the port through fixed facilities, which is not only convenient for operation, but also convenient for safety control, and more convenient for fixed fuel filling facilities to achieve multi-functional services. Suggestion: it should be raised to the agenda for exploration and research.

### *Application Trend And Prospect of Low Carbon Clean Fuel for Ship Power*

On June 24, 2022, the Ministry of transport of China, the State Railway Administration, the Civil Aviation Administration of China, and the State Post Office issued Implementation Opinions. Article (6) of the opinion puts forward the application direction of exploring new power ships such as methanol, hydrogen, and ammonia. Article (12) of the opinions proposes to improve the technological innovation ability of transportation. Promote the application of new energy, clean energy, renewable synthetic fuels and other low-carbon cutting-edge technologies in the field of transportation. On July 1, the guidelines for the application of methanol / ethanol fuels in ships (2022) issued by China Classification Society (CCS) came into force. The implementation of the guidelines can make the preset clean energy power rules to follow. It can be seen from the above official dynamic documents and specifications that this is China's guidance for the application of methanol technology in fishing vessels and general cargo ships.

If we look at the technical support for the application of low-carbon clean fuels, we know that in the process of human energy consumption, we have experienced fuel changes such as charcoal, coal, oil, natural gas, ethanol, etc. In today's energy transformation and development, the synthesis of renewable methanol, as well as hydrogen and ammonia fuels, are being given public hope by mankind and have launched in-depth exploration and application in the current process of energy transformation.

Methanol is a liquid fuel with the highest hydrogen content available to mankind at present. Under normal temperature and pressure, 1 liter of methanol contains 98.8 grams of hydrogen (0.79kgx12.5%); When pure hydrogen is in liquid state at -253 ℃, the hydrogen content of 1 liter is 70.8 grams; Under normal temperature and pressure, the hydrogen content (hydrogen storage density) of methanol is higher than that of electrolytic water under pressure and low temperature cooling.

Ethanol fuel. In view of the fact that the source of ethanol raw materials in China is likely to compete with land for grain, the development of biomass energy processing industry involving grain as raw materials in China has begun to be regulated.

Several applied research institutions in China are organizing research on the proposal of ammonia fuel. Similarly, ammonia fuel, like ethanol, is likely to be required to choose a new production capacity path in China because it competes with grain for fertilizer.

Hydrogen is being raised to a higher level to carry out application research due to the very clean nature of secondary energy. However, due to the multi node challenges of investment intensity, infrastructure construction, safety precautions, strict control and implementation, from the perspective of hydrogen energy sources, there are new ways to seek industrialized applications in China and the world.

Methanol. On the basis of maintaining the basic properties of its chemical raw materials, it is expanding to energy properties. With the energy advantages of low-carbon clean fuels, it is widely used in the field of power combustion and thermal combustion. Methanol fuel is a liquid storage, transportation and filling method at normal temperature and pressure, which can be used as a substitute and supplement for fossil energy.

The mass hydrogen storage density of methanol is 12.5% (125 kg hydrogen / T methanol); 70MPa high-pressure gas cylinder stores hydrogen, and the mass hydrogen storage density is about 4-6%; Low temperature liquid hydrogen (-253 ℃), mass hydrogen storage density is about 7%. The above comparison also shows the advantages and advantages of the coordinated development of methanol and hydrogen energy.

The basic data of this report is based on the manufacturing and operation industries of Chinese fishing boats and general cargo ships and the basic status quo, with reference to the known data in the field of international shipping and the data published by IMO. The data compiled and included in the report will inevitably be different from the actual situation, but the difference will not affect the reader's judgment and practical application. During the editing process of the report, we have consulted a large number of domestic and foreign literatures and publicly published data, and we would like to thank the author and data provider for quoting the original text.

China's methanol power combustion and combustion application technology has matured, and the development of methanol economy is becoming a consensus in the energy field. We hope to carry out technical exchanges and cooperation with our counterparts in the field of energy preparation and energy application all over the world, so as to jointly promote the realization of the overall goal of human carbon and environmental governance.

## This section report was compiled by:

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20th July,2022

## Ammonia as fuel for marine engines

*This section was written by DTI and DTU, Denmark.*

### Ammonia combustion properties

Ammonia has an octane rating of 110-130 RON. This could indicate that ammonia is suitable for spark ignited engines. The laminar flame speed of pure ammonia is however very low, which means that it takes a long time for the combustion to complete, compared to regular gasoline or other fuels.

The slow combustion of ammonia also makes it difficult to ignite and burn in conventional diesel engines. Researchers have successfully experimented with mixing ammonia with more flammable gases, such as hydrogen, methane, and dimethyl ether, to increase the combustion rate. Such combustion principles may be applicable to future engines, but it will require a willingness to handle additional fuels onboard ships, which is not desirable today.

Catalytic decomposition of ammonia to hydrogen and nitrogen could be used to improve the combustion process. Hydrogen can be ignited in a very wide mixing ration with air and has a very high flame speed, which makes it useful as ignition promoter. Research has shown that ammonia can be ignited well when mixed with 10 % (vol.) of hydrogen.

### Plans for ammonia powered ships

As of 2023, no ships are powered by ammonia fuelled engines.

Intentions of building the first ammonia engine powered ship for delivery in 2025 was announced as a Memorandum of Understanding in June 2022 (The Maritime Executive, 2022), by the company Eastern Pacific. Engines will be delivered by MAN, who is currently developing and testing the 2-stroke combustion concept for ammonia.

WinGD has announced a joint development of ammonia engines with the company CMB.TECH. The engines are to be delivered for new ships from 2025.

### Ammonia DF engines under development

The most realistic way to use ammonia for now is in DF engines, with a large quantity of pilot fuel to ensure that the ammonia is ignited and burns to completion. This principle is being developed by engine designers MAN ES and WinGD for 2-stroke engines and may also be developed for 4-stroke medium speed engines.

### 2-stroke ammonia engine development

Marine 2-stroke engines operate at low speeds, typically less than 200 RPM. The low rotational speed of the 2-stroke engine is an important factor, as it improves conditions for ignition and complete combustion of pure ammonia. Ammonia can be ignited by injection of fuel oil, in the well proven DF principle.

In 2022, the 2-stroke division of MAN Energy Solutions started preparing a stationary 2-stroke research engine for combustion of ammonia. The engine design has four injectors per cylinder, with two dedicated for injection of liquid ammonia, while the other two are dedicated fuel oil injection. Ammonia is injected into the cylinder when combustion of the pilot fuel takes place and burns in a diffusion flame type combustion process. In September 2023, MAN announced that they had successfully demonstrated ammonia combustion in their test engine. MAN ES aims at having this principle ready and delivered to a shipyard in 2024.

WinGD is currently also developing DF 2-stroke engines for ammonia. According to press releases, the company has received orders on ammonia DF engines, with delivery planned in the beginning of 2025.

### 4-stroke ammonia engine development

Medium speed 4-stroke marine engines operate at 500-1000 RPM, which makes it even more challenging to develop a combustion principle for a slow burning fuel like ammonia. Development of combustion principles for ammonia in 4-stroke engines is ongoing with large engine designers such as Wärtsilä and MAN, but there is very little specific information available to indicate at which state this development is.

### Emissions and exhaust after-treatment requirements for ammonia engines

Ammonia is envisioned as a future fuel with zero direct emissions of carbon. Eliminating carbon emissions completely from future ships will become an important contribution in meeting the IMO goal of 70 % reduction of greenhouse gases from 2050 (IMO, IMO's work to cut GHG emissions from ships, u.d.).

Ammonia as fuel can potentially reduce not only direct emissions of $CO_2$, but also $SO_2$ and particulate emissions. The specific reductions will depend mainly on the specific engine technology.

#### Emissions from fuel oil pilot combustion

Current development is focused on DF combustion of ammonia with fuel oil pilot combustion, which reduces, but does not eliminate, emissions related to fuel oil combustion.

Fuel oil with very low sulfur content (less than 0.1 % sulfur) for pilot combustion will provide the best conditions for efficient $NO_X$ reduction. Reducing $SO_2$ formation will also help to prevent ABS formation in the SCR, and thereby allow the SCR catalyst to operate at low exhaust temperature, at which point high concentrations of unburned ammonia can be expected.

Future combustion concepts for ammonia may be using other fuels for ignition or enhancing the combustion properties of ammonia, such as hydrogen, methane or DME. This will reduce the emissions further than the current concepts being developed.

#### $NO_X$ and ammonia slip

Demonstration and research concepts with ammonia as engine fuel have previously shown high levels of $NO_X$, which require aftertreatment to meet IMO Tier II/III. High levels of ammonia slip can also occur at specific operating conditions, such as low and medium load.

SCR catalysts can reduce the $NO_X$ with the ammonia present in the exhaust stream. In this conversion, NO reacts with $NH_3$ in the ratio 1:1, to produce water and pure nitrogen. Ammonia can be added to the exhaust to balance the reaction and provide a high reduction rate of $NO_X$, while surplus ammonia leaving the SCR can be oxidized after SCR with a separate catalyst. This way, both pollutants are effectively reduced.

As a safety measure against large leaks, ammonia can also be removed simply with water mist scrubbers, as water binds ammonia very effectively.

#### Nitrous Oxide

The combustion of ammonia may also result in formation of $N_2O$, also known as laughter gas. This gas is a potent greenhouse gas with a GWP of 273 (EPA 2022). With this factor, an exhaust concentration of only 100 ppm will correspond to 2.73 % $CO_2$, which is unacceptable considering that $CO_2$ reduction is the key motivation for using ammonia.

$N_2O$ is a potentially problematic emission since it is more chemically stable than $NO_X$. The exhaust gas temperature will likely be insufficient to convert $N_2O$ efficiently with current known catalysts, and low load operation will present an even larger challenge for $N_2O$ conversion.

Currently, there is very limited knowledge about the levels of $N_2O$ that may be expected from ammonia combustion, and hence the need to develop new catalysts or other processes targeting $N_2O$ is also unclear. Given the challenge of reducing $N_2O$ with catalysts, it is likely that research and development of combustion engines fueled with ammonia will have to improve the understanding of the mechanisms that lead to formation of $N_2O$ and use this knowledge to design the engines and choose combustion strategies that limit formation of $N_2O$ to acceptable levels.

## Ammonia as fuel for fuel cells

High temperature SOFC fuels can utilize ammonia directly as fuel, where it is decomposed into hydrogen and nitrogen internally in the fuel cell. SOFC fuel cells of either oxygen anion (SOFC-O) or proton conducting (SOFC-H) type can be used.

The conversion of ammonia to hydrogen and nitrogen can also be performed before the fuel cell stack. If the gas is cleaned for unreacted ammonia, it may also be used to feed low and high temperature PEM fuel cells, which are sensitive to impurities such as ammonia. (Georgina Jeerh, 2021)

### Emissions and after-treatment requirements with ammonia fuel cells

As with hydrogen fuel cells, only water is produced in the reaction with hydrogen and oxygen. The nitrogen can however react to form NO by reaction of oxygen anions. In SOFC-O type fuel cells, formation of NO with ammonia is avoided by using a catalyst with a low selectivity against NO formation.

Unreacted ammonia from incomplete conversion in external catalytic converters and from direct ammonia fuel cells can be minimized by proper design. Ammonia oxidation catalysts can be used to further reduce ammonia to acceptable levels in the exhaust stream.

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## Ammonia combustion in a small 4-stroke diesel engine

*This section was written by DTU, Denmark.*

Ammonia application in CI engines.

This section describes the investigation carried out at The Technical University of Denmark in relation to IEA Advanced Motor Fuels TCP Task 60. A more detailed description of the experimental results is published elsewhere (Førby, 2023). The purpose with this study was to investigate the performance of ammonia when applied to a compression ignition engine. The goal was to apply as high share of ammonia as possible in a dual fuel concept where the ammonia combustion is initiated with a pilot diesel like fuel.

## Ammonia in combustion engines

Spark-ignition (SI) engines have been demonstrated to operate on ammonia for many years, with important work performed in the 1960's (E. S. Starkman, "Ammonia as a spark engine fuel: Theory and application". In: SAE Transactions 75 (1967), pp. 765–784. DOI: 10.4271/670946., 1967), and renewed interest has increased the research in recent years. Many SI-engine studies have used ammonia mixed with hydrogen for improved combustion stability due to the high flame speed of hydrogen [ (Fredrik R. Westlye, 2013), (Gentili., 2013), (Lhuillier, 2019), (Mercier, 2022), (Mørch, 2010)]. Compared to conventional hydrocarbon combustion, using ammonia generally yields higher NO- and $N_2O$-emissions. $N_2O$ has a global warming potential of 298 with climate-carbon feedback (265 without) (Stocker, 2013), which makes it highly relevant for emission studies. It has been shown that fuel in crevice volumes was essential for nitrogen-based emissions (Fredrik R. Westlye, 2013). Using ammonia as a fuel for compression ignition (CI) engines remains a great challenge due to the high auto-ignition temperature of ammonia – more than 400 K higher than that of diesel at atmospheric conditions (Pavlos Dimitriou, 2019)– meaning that compression ratios higher than 35:1 are required for ammonia-only CI operation [ (Gray, 1967), (E. S. Starkman, "Ammonia as a diesel engine fuel: Theory and application". In: SAE Transactions 76 (1968), pp. 3193–3212. DOI: 10.4271/670946., 1968)]. Other challenges for ammonia operation is the high heat of vaporization, which significantly decreases in-cylinder temperature after injection (Charles G. Garabedian, 1966). Ammonia/air mixtures also have a low flame speed, generally around 1/5 of methane/air mixtures (Kobayashi, 2018), and hence large fuel slips can be observed using ammonia. As mentioned, hydrogen can be used to increase combustion speed. Due to these challenges, most studies regarding ammonia in CI engines are dual-fuel operation (Pavlos Dimitriou, 2019), often using diesel as a pilot fuel.

Reiter et al (Aaron J. Reiter, "Demonstration of compression-ignition engine combustion using ammonia in reducing greenhouse gas emissions". In: Energy and Fuels (2008). DOI: 10 . 1021 /, 2008) used a dual-fuel configuration with premixed ammonia and direct-injected diesel and varied the fuel contributions, first with 10-45 % energy contribution, then later (Aaron J. Reiter, 2010) from 0 % (diesel only) to around 80 %. Among their key findings were that small amounts of ammonia energy yielded high brake-specific fuel consumption (BSFC) of ammonia due to very lean ammonia-air mixtures, while high ammonia energy showed high BSFC of diesel due to low temperatures. They also found that using small amounts of ammonia (eg. 5-20 %) decreases the in-cylinder temperature resulting in decreased NO-emissions and increased and CO-emissions, compared to diesel-only. Larger amounts of ammonia energy (>50 %) significantly increased NO emissions due to fuel-bound nitrogen. However, another study with port-injected aqueous ammonium and direct-injected diesel (Frost, 2021) showed the opposite trend of Reiter's results regarding NO-emissions: as ammonia contribution was increased from 0 % to 10 % energy-contribution, the NO-emissions initially increased due to fuel-bound nitrogen, while larger amounts of ammonia (to 25 %) showed a decrease in NO due to lower temperatures.

The vapour pressure of ammonia is similar to that of dimethyl ether (DME), which has a cetane-number higher than that of diesel, and this makes it attractive to improve the CI combustion properties of ammonia by mixing it with DME for a single-fuel CI-operation. Gross (Christopher W. Gross, 2013) found that, compared to 100 % DME, the ammonia-DME mixture showed higher CO- and NO-emissions due to low temperatures and fuel-bound nitrogen, as well as higher ignition delay and cyclic variations. Another study (Kyung Hyun Ryu, 2013), also employing a DME-ammonia mixture, with up to 60 % ammonia, showed similar results. With 60 % ammonia very early injection, -340 to -90 CAD ATDC (Crank Angle Degrees After Top Dead Center) was necessary, which showed HCCI (Homogeneous Charge Compression Ignition) combustion with very abrupt heat release and high cyclic variations at low loads due to incomplete combustion, which also dramatically increased hydrocarbon- (HC) and CO emissions. A spark-assisted compression ignition (SACI) operation has recently been shown to run on neat ammonia (Mounaïm-Rousselle, 2021). SACI uses a spark for early partial combustion to increase the temperature, enabling compression-ignition for the main combustion. However, the two phases were not distinguished, and SI-like operation was obtained.

## The DTU CI engine setup

In this investigation, a dual-fuel concept with premixed ammonia and direct-injected n-heptane ($C_7H_{16}$) was applied, and ammonia-energy contribution was varied from 80-98%. The high ammonia-energy was possible by using a GDI (Gasoline Direct Injection) nozzle and using n-heptane as the pilot fuel, since this has low viscosity and high cetane number. Some representative values of viscosity and cetane number for both diesel and n-heptane are shown in Table 28. Using a more viscous pilot fuel make very small injections difficult with the GDI nozzle and yield larger spray droplets.

*Table 28 Viscosity and cetane numbers of diesel and n-heptane for comparison. *Minimum cetane number and cetane index is 51 and 46, respectively, in EN 590 diesel fuel standard. **Multiple values presented without specification of cetane number or index.*

| | Diesel | n-heptane |
|---|---|---|
| **Kinematic viscosity [mm$^2$/s]** | 3.8 [23] | 0.57 [24, 25] |
| **Cetane number** | >51* [26] | 53-56** [27] |

The engine tests were performed with a BUKH DV 24 ME, a 2-cylinder compression-ignited diesel engine with a total displacement volume of 964 cc , a compression ratio of 18 and a maximum power of 17.6 kW from the factory. One cylinder was unchanged and thus operated normally with diesel, while the test-cylinder operated on ammonia as described here. Having a normally operating diesel-cylinder was useful for both motoring purposes, engine start-up and for altering fuel injection in the test cylinder without unstable operation.

For the test cylinder, gaseous ammonia was aspirated into the intake manifold, and n-heptane was injected directly into the cylinder as a pilot fuel to ignite the ammonia-air mixture. n-heptane start of injection (SOI) was 20 CAD BTDC (Crank Angle Degrees Before Top Dead Center) (except when stated otherwise). Earlier SOI – eg. 100-50 CAD BTDC – would result in HCCI-like operation, which was not the purpose of these experiments. As the test engine was not equipped with a common rail system, the n-heptane was pressurized by liquid nitrogen. Due to limitations on the fuel pump, a max. pressure of 120 bars was used. Emissions of certain species (CO, $CO_2$, NH3, NO and N2O) were measured using Fourier Transform Infra-Red (FTIR) measurement. An illustration of the test engine setup is shown in Figure 64.

Pressure data was obtained by means of a pressure sensor located as illustrated in the experimental cylinder. The rate of heat release ($Q_{HR}$) was then calculated from the pressure data the usual way, derived from the first law of thermodynamics:

$$\dot{Q}_{HR} = \dot{Q}_{HR,net} + \dot{Q}_{wall}$$

$$\dot{Q}_{HR,net} = \frac{\gamma}{\gamma - 1} \cdot p \cdot \frac{dV}{d\theta} + \frac{1}{\gamma - 1} \cdot V \cdot \frac{dp}{d\theta}$$

($\gamma$, p, V, $\theta$ = isentropic heat capacity ratio, pressure, volume, crank angle degree)

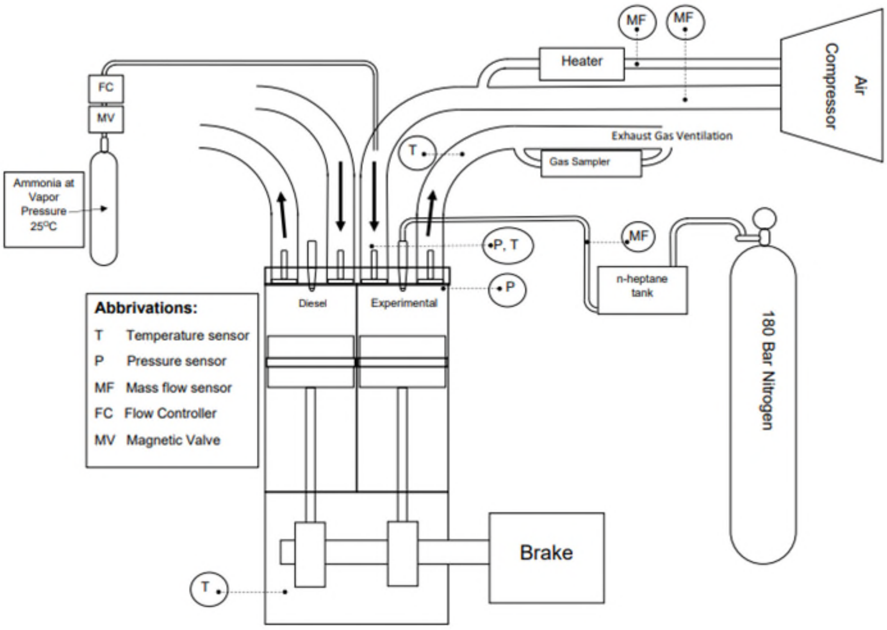


*Figure 64 DTU Test engine set-up.*

## Results

Figure 65 shows the rate of heat release observed when increasing the ammonia energy share from 80% to 98,5% with a constant overall λ = 1,1 (excess air ratio), by decreasing the pilot fuel flow and increasing the ammonia flow. It was chosen to keep the global λ and Start Of Injection (SOI) constant, and consequently allow some variation in IMEP (Indicated Mean Effective Pressure) with changing energy contributions, because the purpose of the study was investigating the ignition and combustion processes. For engine concept feasibility the IMEP should be constant while using maximum brake torque SOI. The value of λ = 1,1 was chosen from initial studies showing high indicated efficiencies at this value. The high ammonia-energy was possible by using a GDI nozzle and using n-heptane as the pilot fuel, since this has low viscosity and high cetane number

With 80 % ammonia energy, a brief initial peak in heat release rate can be identified before a longer and slightly lower heat release rate takes place. The initial peak is most likely combustion of pilot fuel, and the longer and lower heat release is ammonia combustion. As the ammonia energy is increased – and the pilot fuel is correspondingly decreased – the initial peak decreases, as should be expected. As the amount of ammonia is increased, the ammonia combustion is seen to reach higher heat release rates. The corresponding integrated heat releases are shown in Figure 66, normalized by the total fuel energy injected. An important result obtained from Figure 66 is that the higher levels of NH3 result in a more complete combustion, as a larger share of the fuel energy is extracted through heat release. Related to this, the ammonia slip is shown in Figure 67, where it is seen to decrease with a higher ammonia energy share. Since the increased ammonia energy means an increase in total amount of ammonia and increased ammonia concentration, this should also mean more fuel in crevice volumes. For this reason, it is interesting that the ammonia-slip is reduced with higher ammonia energy, clearly indicating a better ammonia combustion with higher ammonia content. The reason for this is discussed elsewhere, (Winther, 2022).

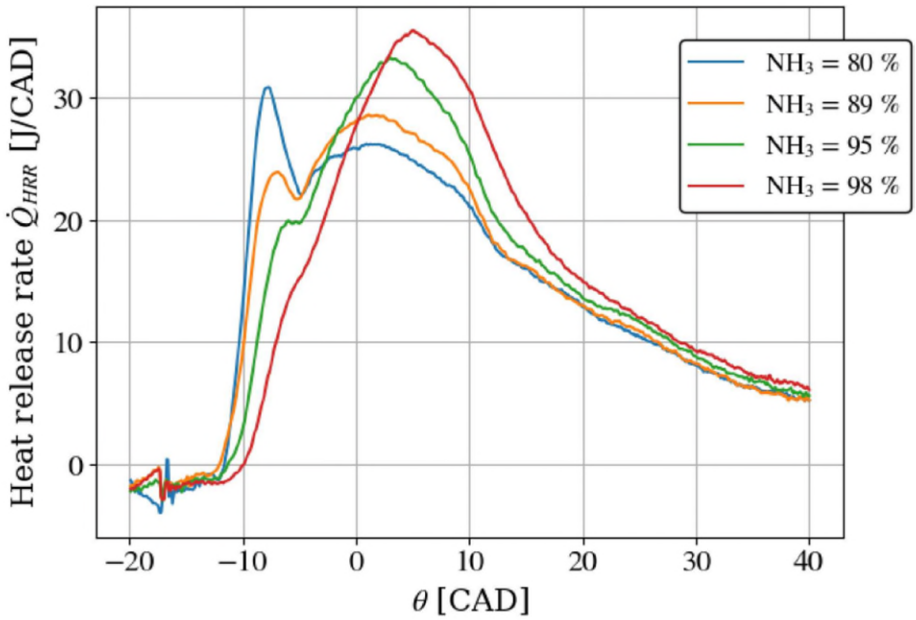


*Figure 65 Heat release rates for increasing ammonia energy, with a constant λ = 1.1*

## Summary

The investigation has shown that it is possible to apply high share of ammonia in a CI engine. As high as 98% ammonia was applied successfully in a dual fuel concept, and the indicated efficiency for this concept was actually higher, compared to operation with diesel fuel on this engine. 98% ammonia is a much higher ammonia share than anticipated, based on earlier studies.

The combustion efficiency increased with higher share of ammonia in relation to pilot fuels in the range 80% - 98% ammonia.

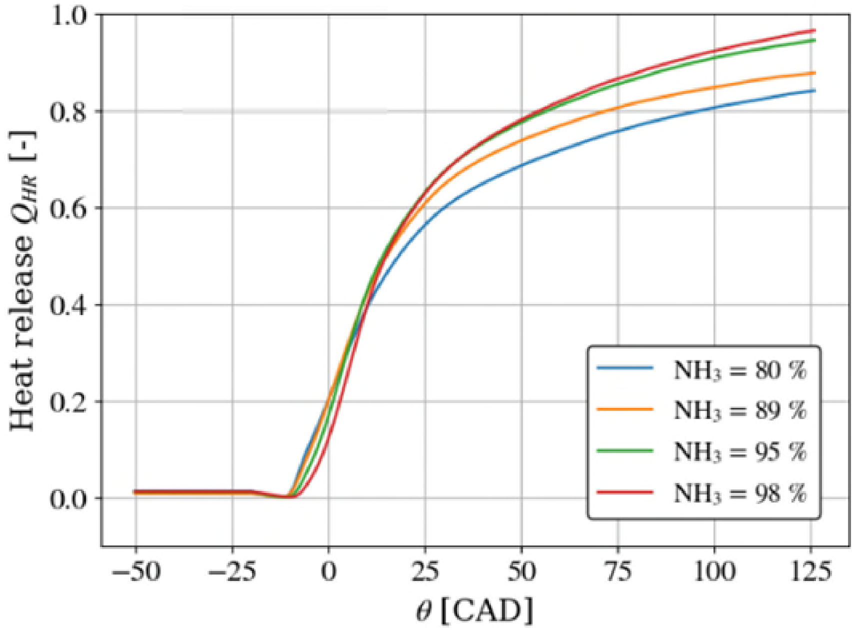


*Figure 66 Integrated heat release curves with increasing ammonia energy and constant λ = 1.1, normalized by the total fuel energy and shifted to begin combustion from 0 heat released.*

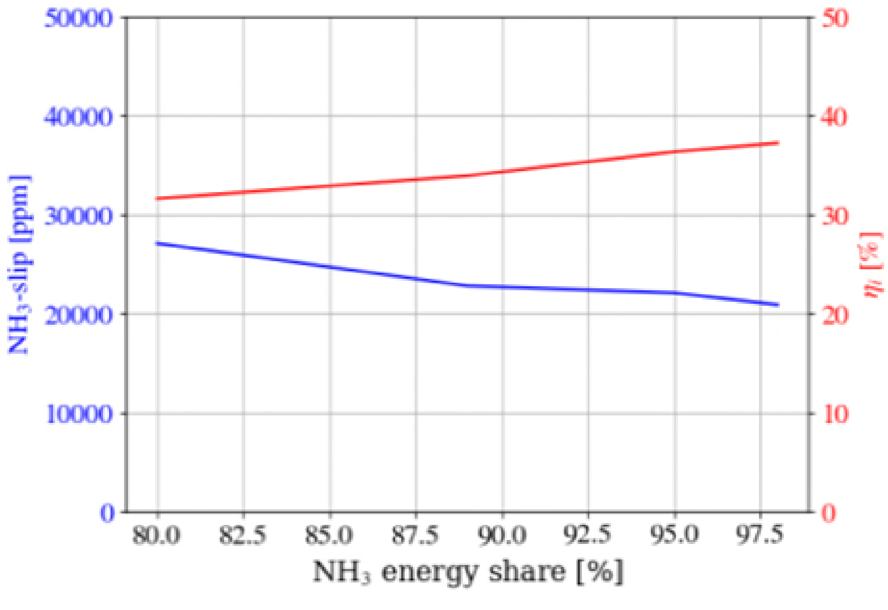


*Figure 67 Ammonia-slip and indicated efficiency $\eta_i$ vs. ammonia energy share with constant λ = 1.1. $\eta_i$=28,3% with pure diesel operation)*

## Ammonia for gasoline-type engines

*This section was written by KSOE, Korea.*

Since the critical threat of the climate change shadow grows year by year, it is not a surprise that instead of choosing gasoline or diesel engines one might select better candidates to deal with future mobility, resource equity and environmental sustainability altogether. In the transportation sector, ammonia, as a carbon-free fuel, is on the spotlight to sort things out in terms of GHG emission problems. Ammonia, adequately used, does not generate any GHG even in commercialized combustion systems.

Ammonia fuel was investigated to replace gasoline through the conversion of a conventional gasoline engine with ammonia fuel system. Though the flame speed of ammonia is 5 times lower than gasoline, the ammonia-gasoline dual fuel shows enhanced combustion characteristics because gasoline acts as a combustion promoter and brings about faster combustion of all the cylinder charge. To this end, an ammonia-gasoline dual fuel system was constructed and a programmable engine controller was also developed to make both ammonia and gasoline injected separately into the intake manifold in liquid phases.

Although ammonia showed 55% lower energy content than gasoline, the ammonia-air mixture at a certain volume denoted quite comparable strength compared to gasoline. The reason for this response was based on ammonia requiring less air quantity. Thus, theoretical air to fuel ratios of 6 could be employed, which are only 40% of gasoline, hence enabling similar mixture power as that of gasoline on a combustible mixture basis.

Measured torque outputs at full load condition were also comparable for both cases, i.e. dual-fuel and pure gasoline combustion, with up to 70% of ammonia energy fraction. Above that fraction, clear evidence emerged about the incomplete combustion of ammonia, producing large quantities of unburned ammonia slip, thus decreasing power output. Although the spark timing was advanced up to 40 degrees BTDC to have similar trends in pressure rise or power output as in the combustion of pure gasoline, it was evident that beyond 70% the process was sacrificed.

The test engine showed quite good performance in terms of power output and emissions with high ammonia fraction. As a result, ammonia was used as main fuel to replace 70% of gasoline and the same amount of carbon emission such as $CO_2$, CO, THC reduced in the engine out emissions. After the installation of the ammonia-gasoline dual fuel system into the test engine, a prototype vehicle named ‘AmVeh’ was built and run successfully to demonstrate ammonia as a carbon-free fuel at the ready.

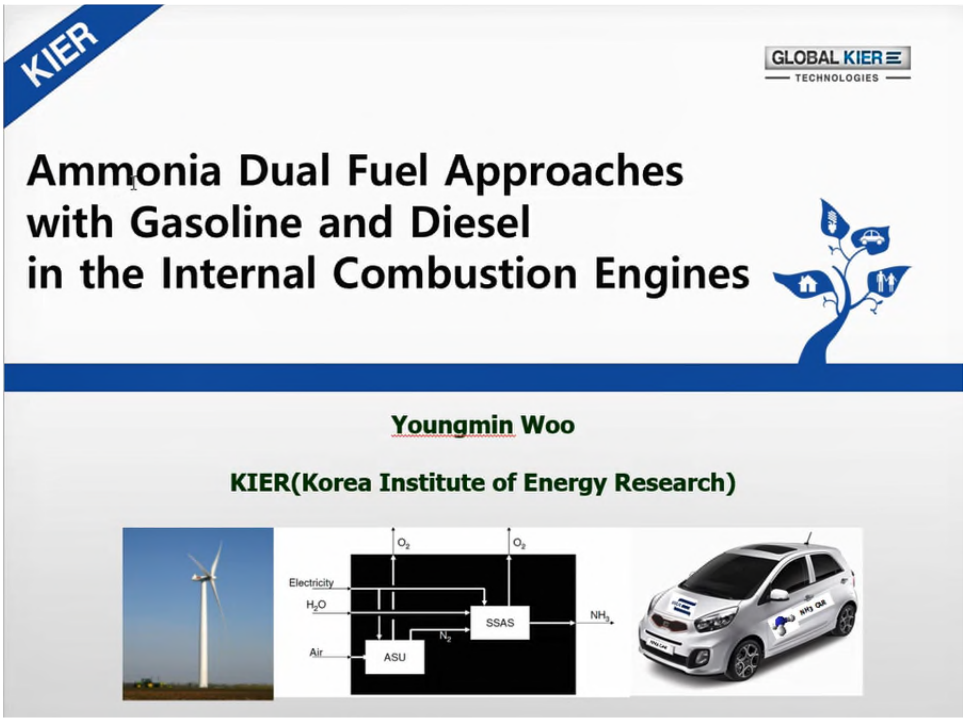


Figure 68 Korean research program focused mostly on gasoline engines.

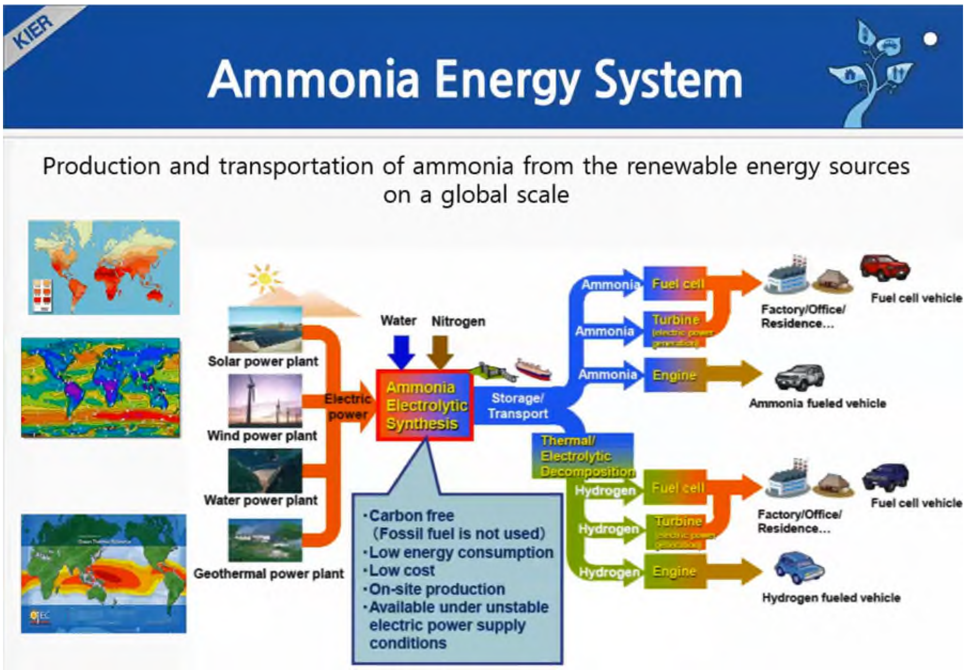


Figure 69 Ammonia can serve directly as a fuel or as a hydrogen carrier.

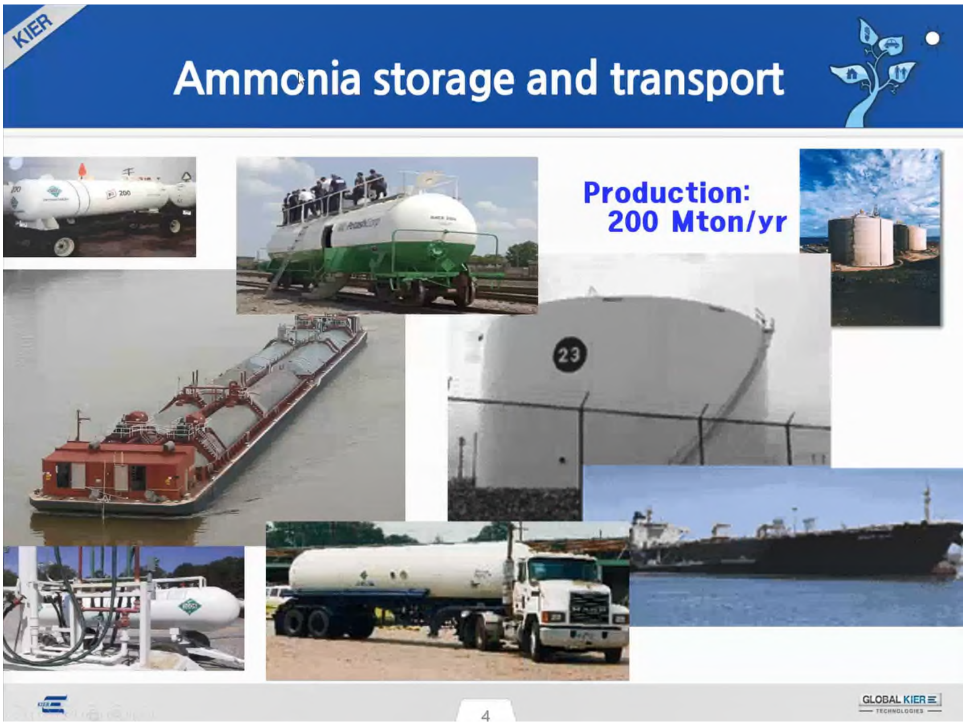


*Figure 70 Ammonia is a common and widely available chemical.*


*Figure 71 Ammonia was used as fuel for trucks, buses and rocket planes in the past.*


*Figure 72 Ammonia can be used in dual-fuel applications with gasoline or propane, or directly in hydrogen engines by reforming of $NH_3$ to $H_2$.*

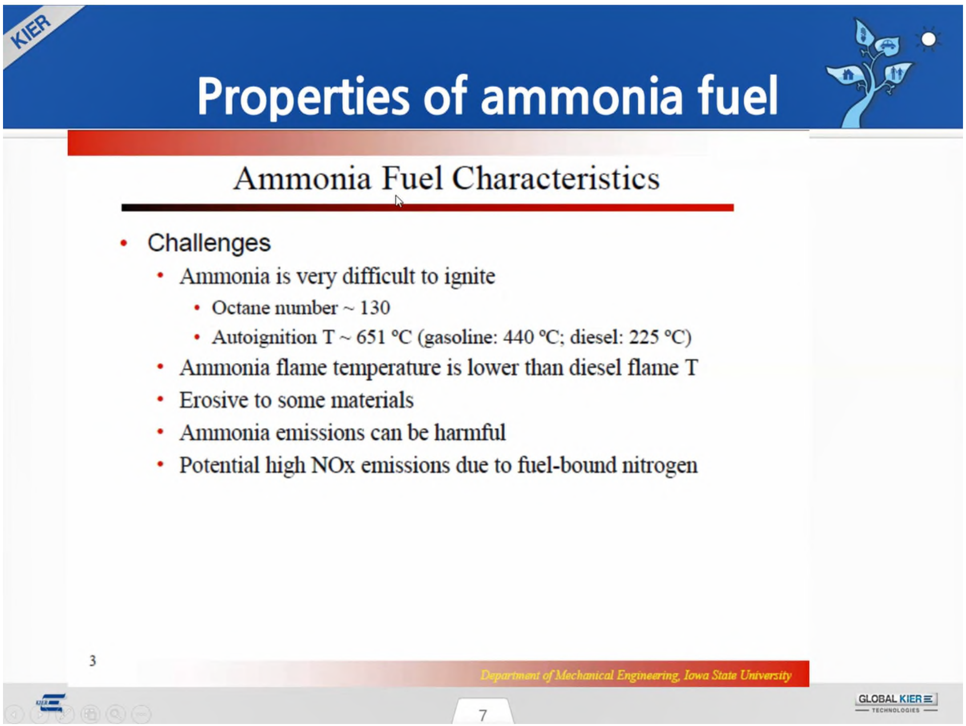


*Figure 73 Some challenging properties of ammonia as a fuel.*

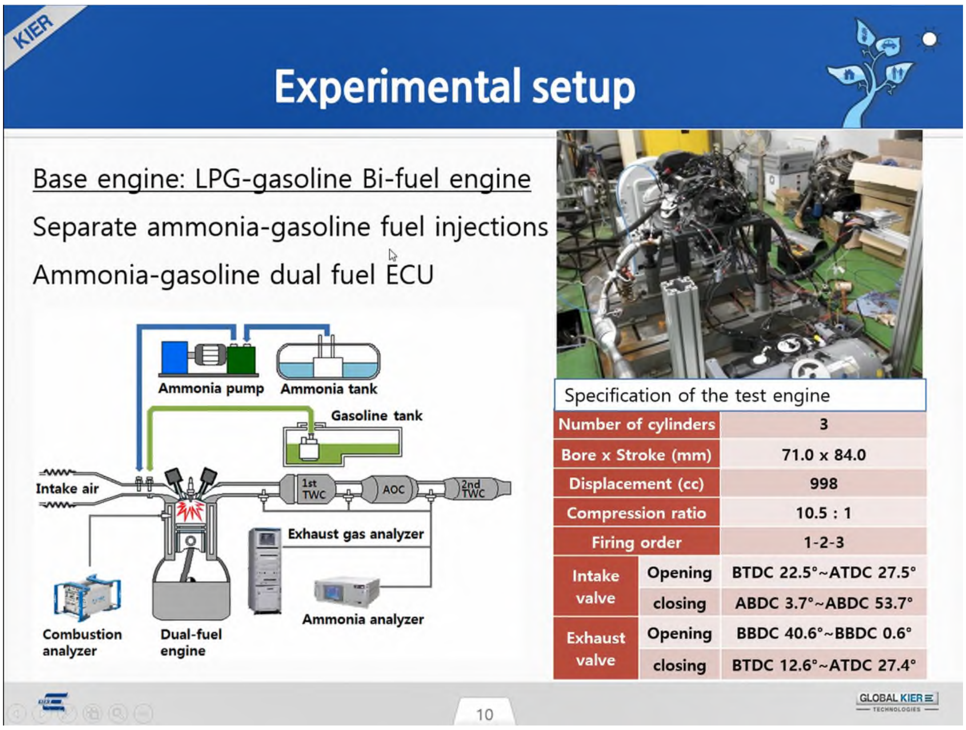


*Figure 74 A dual fuel stoichiometric port injected ammonia-gasoline engine.*

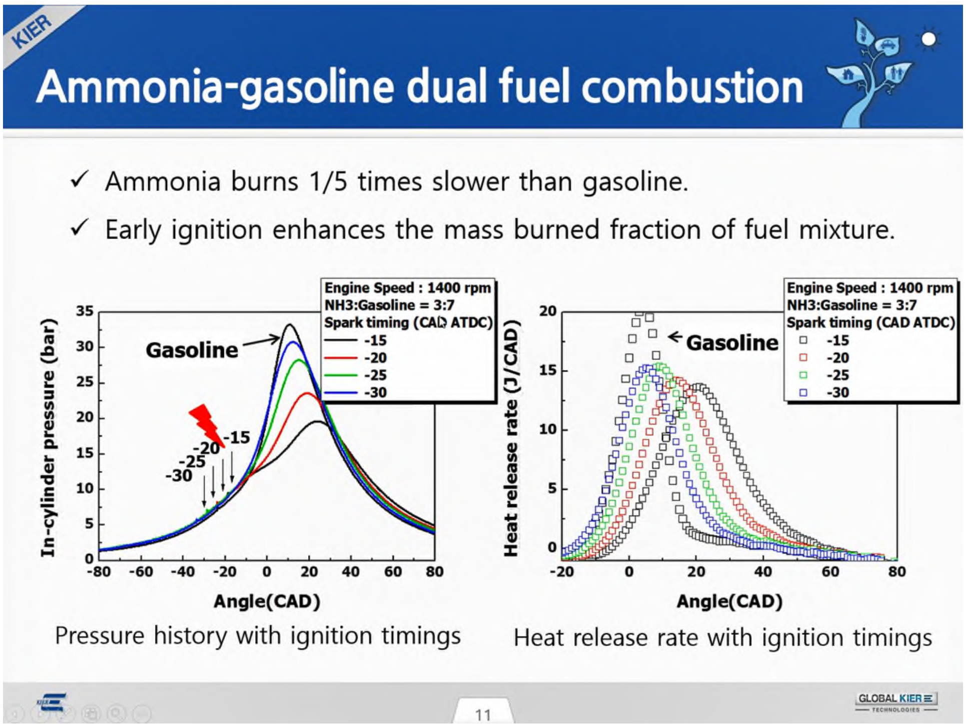


*Figure 75 Slow burning is a principal feature of ammonia when used as a fuel.*

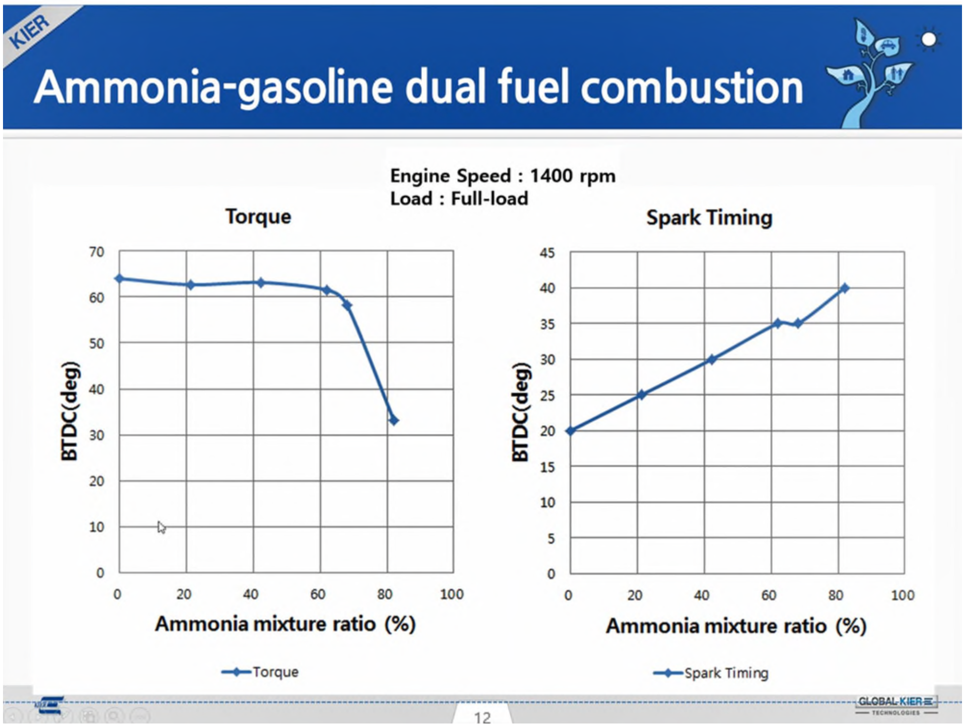


*Figure 76 Mixtures above 60% ammonia reduce engine performance.*

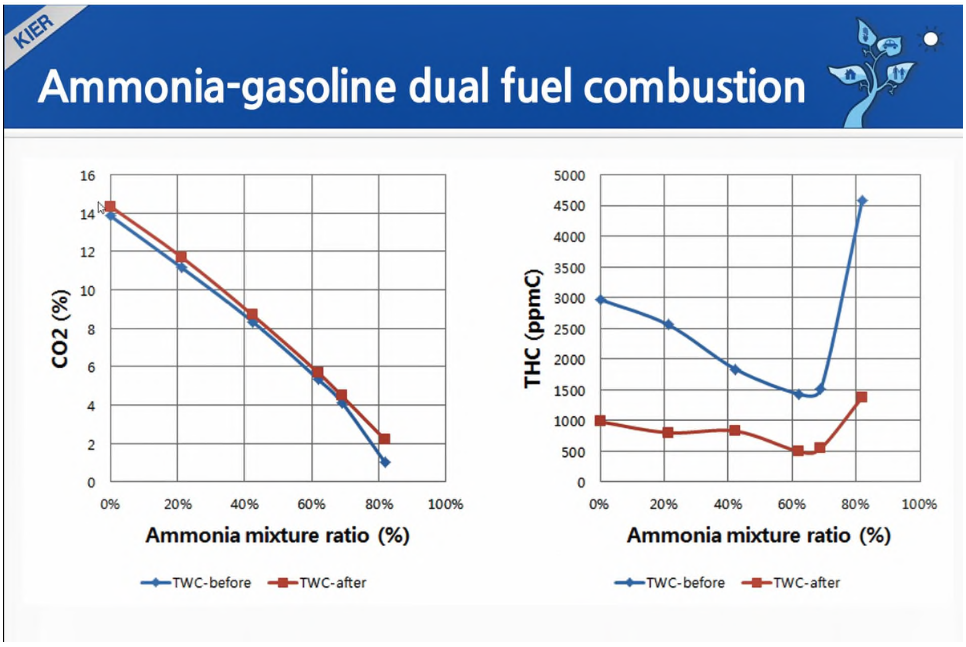


*Figure 77 Mixtures above 60% ammonia lead to higher unburnt hydrocarbon emissions.*

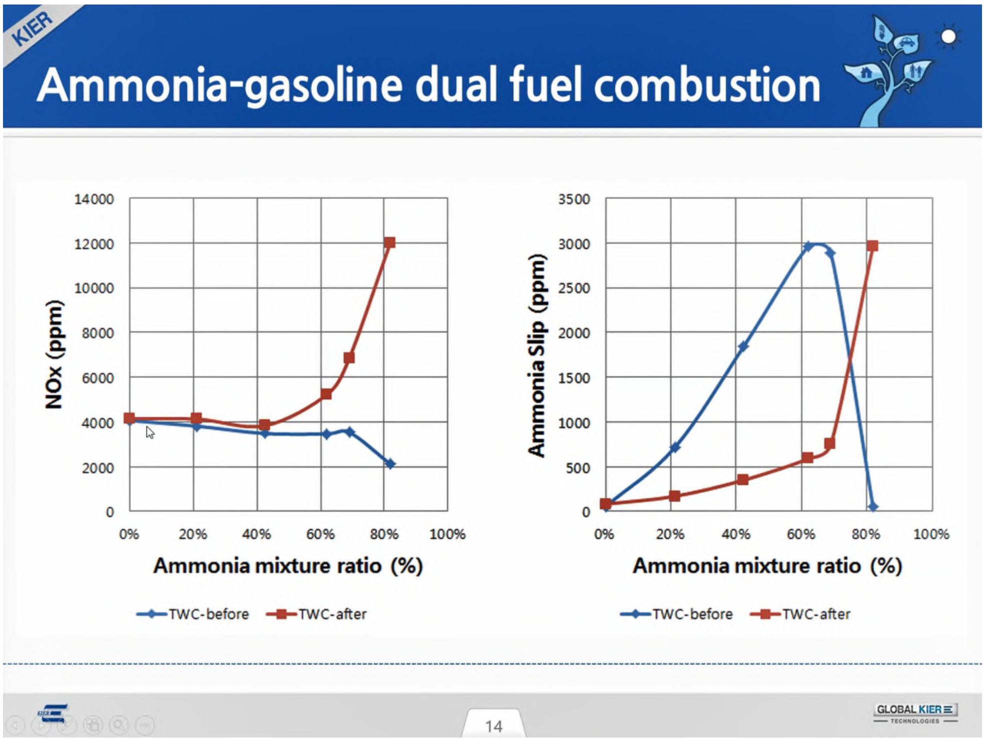


*Figure 78 Mixtures above 60% ammonia lead to higher NOx and ammonia emissions.*


*Figure 79 A working dual fuel ammonia-gasoline vehicle.*

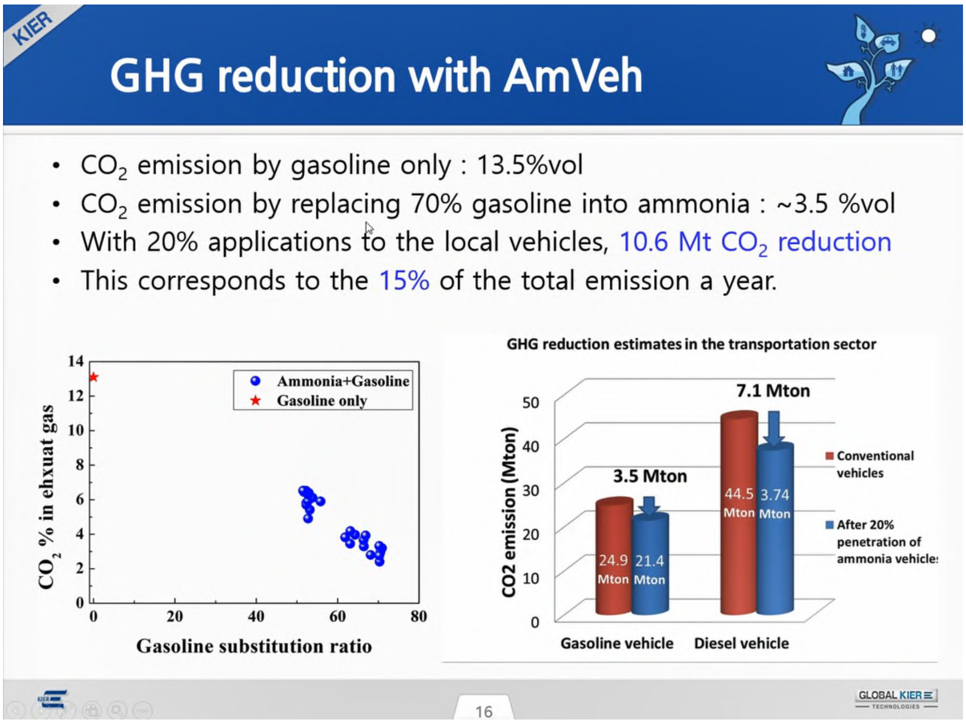


*Figure 80 Engine-out $CO_2$ can be reduced by roughly 70% with ammonia.*

## Hydrogen as a marine fuel

*This section was written by DTI, Denmark.*

The most recent statistics provided by DNV AFI show that only 4 vessels are registered as operating with hydrogen. 3 of these are using hydrogen in DF engines with diesel pilot ignition, the last is using hydrogen fuel cells. 6 more ships with DF engines are on order and 17 ships are to be equipped with hydrogen fuel cells for delivery until 2028.

Military vessels such as small submarines, which are not included in the statistic, are known to be equipped with PEM fuel cells, which are powered by liquid hydrogen or methanol. These fuel cells provide longer range than traditional battery solutions, and provide stealthy operation, which is crucial to submarines, even when operating at surface level.

With the inherent difficulties and safety issues related to handling and storage of hydrogen, it has not been considered as a feasible alternative fuel for ships until very recently.

### Hydrogen storage

The heating value of hydrogen is about 120 MJ/kg, which is approx. three times higher than marine fuel oil. The density of hydrogen is however very low. Onboard storage of hydrogen requires either carbon fiber reinforced cylinders with 350-700 bar of pressure or cryogen storage tanks at -253 °C (20 Kelvin). Both solutions are expensive, but cryogen storage is likely the safest and most cost efficient for large volumes of hydrogen.

### Onboard conversion of hydrogen from ammonia

Hydrogen may be produced onboard by catalytic cracking of ammonia. In this case, the fuel stream will contain both hydrogen, ammonia, and nitrogen, which can either be purified further and used for fuel cells or supplied to a combustion engine as a mixture.

PEM Fuel Cells generally require high purity hydrogen and are sensible to exposure of ammonia. The company RenCat (now acquired by Alfa Laval) has developed and patented technology for cracking ammonia and purification of hydrogen for fuel cell application.

In a combustion engine, the mixing ratio of hydrogen and ammonia can be used to control the combustion behavior to match the operating condition, e.g., by controlling reaction speed to limit combustion pressure.

### Hydrogen as fuel for fuel cells

When hydrogen is used in a fuel cell it combines with oxygen in an electrochemical process that produces electricity. Fuel cells have a thermal efficiency of 50-60 % depending on the load. The conversion of hydrogen produces water vapor as the only biproduct, and fuel cells do therefore not require any exhaust after-treatment.

Low and high temperature PEM fuel cells are arguably the most efficient way to produce power from hydrogen in small scale applications and vehicles. PEM fuel cells are however dependent on expensive catalyst metals and require high purity hydrogen. For large power demands a more economical solution may be found with high temperature SOFC fuel cells, which are based on less costly ceramic materials. The SOFC cells are more tolerant to fuel impurities but are more fragile and susceptible to wear and damage from thermal cycling.

The Norwegian ferry M/F Hydra (NORLED, u.d.) is powered by 2x 200 kW fuel cells with liquid hydrogen onboard.

The largest hydrogen vessel announced to date will be a DFDS ferry (DFDS, 2020) (Europa Seaways), which is planned to be powered by a 23 MW hydrogen fuel cell system. The ferry is planned to operate between Oslo and Copenhagen from 2027, with a capacity of 1800 passengers and 380 cars or 120 lorries The build is however relying on funding from EU, which is currently not secured.

### Hydrogen as fuel for combustion engines

Hydrogen has excellent ignition and combustion characteristics, which makes it suitable as a pure fuel in combustion engines operating with premixed combustion. Hydrogen has a very wide flammability limit, which makes it possible to operate with very lean mixtures and hence low loads.

In marine engines, hydrogen can either be utilized as substitute for methane (LNG) in spark ignited 4-stroke engines, or in dual fuel solutions instead of LNG, with fuel oil or biodiesel as ignition source.

The company CMB.TECH has modified engines for dual fuel operation with hydrogen, which is installed on 2 crew transfer vessels and 1 tug.

#### Emissions with hydrogen as fuel for combustion engines

Combustion of hydrogen in combustion engines produces mainly water, but also some $NO_X$ due to the high in-cylinder temperature. The $NO_X$ can be removed with SCR or reduced to acceptable levels with internal or external EGR.

Hydrogen combustion does not result in PM, $SO_X$ or volatile organic emissions. After-treatment with SCR or efficient EGR management will therefore result in a very clean exhaust gas.

# Liquefied gases (LNG/LEG/LPG) as marine fuels

*This section was written by DTI, Denmark.*

In the last two decades, LNG has taken a leading role as a clean burning alternative to fuel oil in new ships.

New ships designed to operate partly or fully in ECAs must comply both with the fuel sulfur limit and the IMO Tier III regulation. For engines designed for high-sulfur fuel oil operation, they must be equipped both with an EGR/SCR solution and a $SO_X$ scrubber.

Today, LNG may represent an acceptable alternative to continued use of fuel oils to many ship owners. LNG eliminates the need for $SO_X$ removal by scrubbers and improves the operating conditions and lifetime of the SCR systems used for Tier III compliance. It also improves the EEDI (energy efficiency design index) for new ships, compared to fuel oil.

## Definitions of liquid gases

LNG (liquefied natural gas) consists mainly of methane, with minor concentrations of ethane and trace amounts of other gases. It is used mainly as a general-purpose fuel for heating and power production. It is transported from production sites in liquid state in large carrier ships and distributed as a gas in large networks across many developed countries in the world.

LEG is liquefied ethane gas, which is a high purity product used mainly for production of ethylene, which again is used for production of plastics.

LPG is liquefied petroleum gas, consisting of butane and propane. It is used as fuel in many applications such as heating, cooking and as fuel for some engines used in trucks and light vehicles.

LNG, LEG and LPG have excellent ignition and combustion properties and can be used in marine engines. The most common engine types using LNG as fuel today are the DF engines (both 2 and 4-stroke), which use a diesel pilot injection to ignite the methane. Some ships, however, use monofuel SI LNG engines, which are not capable of using other fuel types.

The most common fuel type of the above is LNG, which will be the focus for the rest of this chapter. LEG and LPG are used mainly as fuel on gas carriers transporting these gases, with 2-stroke DF engines designed specifically for these gas types.

## Storage of liquid gases

LNG is stored in cryogenic tanks onboard in its liquid state at around -162 °C, with a permissible vapor pressure of 25 kPa. The gas is evaporated and pressurized before use in 2-stroke and 4-stroke dual fuel engines which propel the ship.

LPG and LEG are also stored in liquid state at low temperatures. LEG is liquid at around -89 °C and LPG at -42 °C, which is the boiling point of propane.

## Background for use of LNG in ships

Natural gas has been used as the primary fuel for many years in LNG carriers, which utilize boil-off gas (BOG) for their engines. Until the late 1990s, the standard solution was to burn evaporated gas in boilers, which provided steam for steam turbines.

From around the year 2000, new-built LNG carriers were equipped with large 4-stroke DF engines, which were more efficient than the steam turbine solutions. In 2015, even more efficient 2-stroke dual fuel engines became available for new ships.

The 4-stroke DF engines used for LNG carriers were also used for offshore supply ships and other medium sized ships such as ferries in Norway, starting from 2003.

### State of use

Since 2015, when the first 2-stroke DF engines for LNG became available, the market for LNG powered ships has grown rapidly.

DNV AFI provides a detailed insight into the specific ship types which use LNG. The statistics do not include LNG carriers and floating LNG production units and terminals, which also use LNG as fuel for their engines. Figure 81 provides an overview of number of operational and orders 5 years ahead for LNG powered ships, excluding the carriers.

Detailed statistics on LNG powered ships and LNG carriers are instead available on the website sea-lng.org (SEA-LNG Ltd., 2020) . According to sea-LNG, approximately 10-20 % of all new ordered ships are to be powered by LNG.

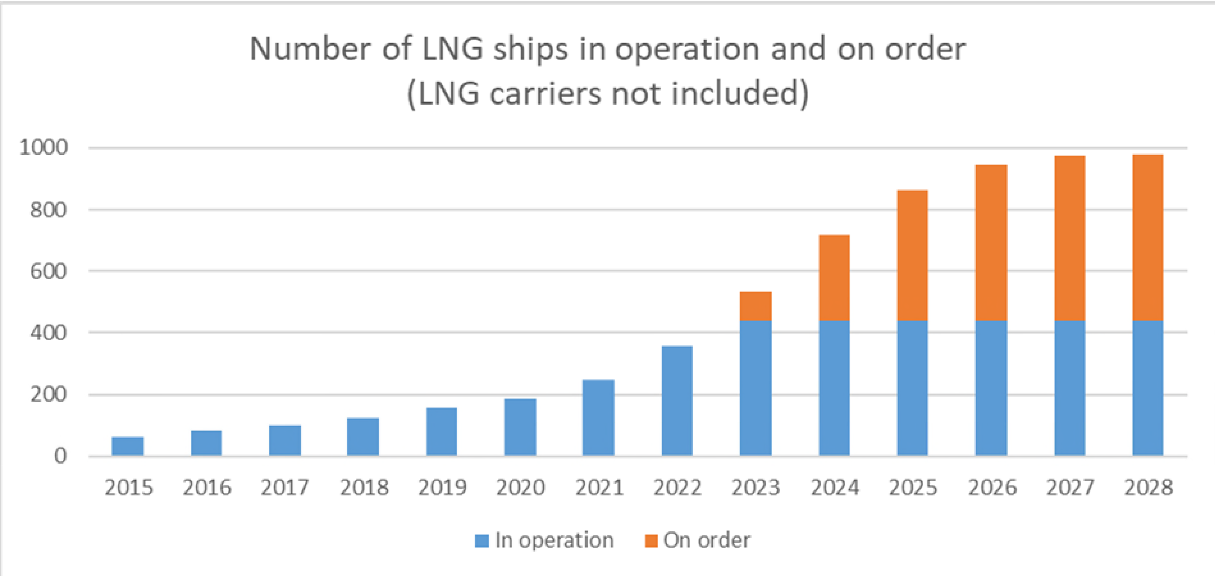


*Figure 81: LNG fueled ships in operation and on order (excluding LNG carriers)*

### Engine types

DF 2-stroke and 4-stroke engines are designed to operate with LNG but can also use fuel oil as the primary fuel if LNG is not available. The DF engine is the most common choice for all ship types.

Monofuel gas engines are designed with a prechamber solution, in which a spark plug ignites a stoichiometric fuel/air mixture. The resulting combustion is used for ignition of the premixed lean cylinder charge. These engines cannot switch to using fuel oil. Some of the large vessels with monofuel engines are passenger ferries owned by shipping companies Fjord Line and Stena Line. These ships operate in the North Sea and Baltic Sea ECAs without exhaust aftertreatment of $NO_X$ or $SO_X$.

#### LNG Ready and retrofitting for LNG DF

LNG Ready is a term for ships that are technically prepared for later conversion to LNG dual fuel operation. This preparation is made to many ships since it is generally less expensive to make these preparations during construction rather than as a full retrofit later. The LNG ready ships are included in the DNV AFI statistics for LNG fuelled ships, so the number of ships operating with LNG is somewhat lower than indicated above. Please refer to further information at DNV, which is the leading company for classification for LNG powered ships.

As of 2023, only 20 ships globally have been retrofitted for operation with LNG, and only 5 more retrofits are ordered. It is generally a very comprehensive task to retrofit the installations for LNG, including tanks, safety measures and engine modifications. This means that the advantage in terms of fuel cost savings must be significant for a retrofit to be performed with existing ships.

## LNG infrastructure ship types

### LNG carriers

Currently, the world fleet of LNG carriers counts around 640 ships. These carriers transported around 370 million tons of LNG from production sites to consumers in 2021 (Internatinal Gas Union, 2022), which makes LNG one of the largest markets for product transportation.

Most LNG carriers are very large vessels. The average LNG carrier transports between 125,000 and 150,000 $m^3$ of LNG, and the largest can transport up to 266,000 $m^3$ of LNG.

The carriers commonly use the same LNG that they transport as cargo, as fuel for their DF engines.

### LNG infrastructure vessels

In addition to the LNG carriers, around 39 LNG bunker vessels are currently in service, with 18 more orders confirmed. These are part of the fuelling infrastructure for LNG powered ships, with great importance in regions were land-based LNG refuelling infrastructure is not in place.

Distribution of LNG to shore is often performed by ships directly to shore terminals which feed the gas into the natural gas grid. Around 50 ships are specifically built for regasification of the liquid LNG, which should otherwise be performed at shore-based terminals. The motivation for using ships is not only the flexibility of this solution, but also because shore terminals are very expensive and takes years to build. The term used for these vessels are FSRU (Floating Storage and Regasification Unit). They are in many cases decommissioned LNG carriers, which are rebuild for the task of regasification.

The LNG carriers and FSRU ships now play a critical role in supplying Europe with LNG, to replace the natural gas which was previously supplied in pipelines into the EU from Russia. About 25 FSRU ships have been leased by EU countries, in preparation for an increase in LNG deliveries to Europe from gas fields in Qatar and the US.

### Transport of LEG and LPG

LEG and LPG are transported at sea as cryogenic liquid in large volume carriers. The transported volume is however not as large as LNG. According to DNV AFI, there are currently 87 LPG carriers and 9 LEG carriers, which are comparable in size and operating principle to the LNG carriers. They also use the cargo as fuel, with engines that can use either LPG or LNG

As fuel, LPG and LEG have the same advantages in terms of emissions as LNG, with zero sulfur and low $NO_X$ (Berg, 2021). In addition, emissions of unburned fuel from LPG and LEG do not have a strong greenhouse effect like methane.

## Emissions and exhaust after-treatment requirements for DF gas engines.

LNG has been used as marine fuel for more than 20 years in ships, as a cleaner alternative to fuel oil and to reach compliance with IMO $NO_X$ and $SO_X$ regulations. $NO_X$ compliance, however, depends on the specific engine technology.

### Tier III compliance

4-stroke DF engines operate with premixed lean combustion of natural gas, which results in a low formation of $NO_x$ that does not require after-treatment. These engines are therefore Tier III compliant when operating in DF mode with LNG as the primary fuel.

2-stroke DF engines with direct high-pressure injection operate with a diffusion-controlled combustion, which leads to $NO_X$ formation comparable to fuel oil combustion. These engines require after-treatment by SCR or EGR to reach Tier III compliance.

2-stroke DF engines using low-pressure gas admission concepts burn the gas in a lean premixed combustion (Otto principle) which reduces NOx formation. These engines are equipped with EGR as standard, which is sufficient for Tier III compliance.

2-stroke DF engines designed for LPG or LEG also operate with direct high-pressure injection and must use EGR or SCR for Tier III compliance.

### $SO_X$ compliance

Due to the absence of sulfur in LNG, DF engines using LNG also automatically satisfies the sulfur limit in ECA zones. The DF LNG engine can therefore be a cost-effective solution to ensure both IMO Tier III and sulfur compliance in ECA zones, as an alternative to using monofuel diesel engines with LSFO and SCR catalysts.

While LNG does not contain sulfur, the fuel used for pilot combustion does. The amount of fuel oil used in pilot combustion is however normally only around 5 %, which means that the emissions will be sulfur compliant in ECA zones even with 0.5 % S fuel in pilot injections.

The fuel carriage ban ensures that the ship emissions will be compliant in cases where LNG cannot be used, e.g., due to fuel system failures that prevent fueling the engines with LNG. Ships without scrubbers are not allowed to carry fuel oil with more than 0.5 % S in international waters and must also carry 0.1 % S fuel for operation in ECA zones. LNG powered ships will therefore generally not have a requirement for $SO_X$ scrubbers.

### PM emissions

LNG combustion reduces emissions of particulate matter, both in dual fuel engines and in pure gas engines. Methane burns with very low formation of soot in dual fuel combustion. The soot is mainly produced by pilot oil and lubrication oil combustion.

It may be argued that particulate filters are possible but unnecessary with LNG ships. They may however be relevant for reducing emissions from certain ship types, such as passenger ferries or cruise ships, to levels which are comparable to vehicles.

### Methane emissions

Despite being a very clean fuel, LNG can also result in relatively high emissions of methane, a strong greenhouse gas with a GWP of about 86 in a 20-year time frame. Methane emissions can occur when the natural gas is extracted, cleaned and liquified, and in the transport chain. Some engine types are also known to have slips of methane in the order of 1-5 % of the methane supplied to the engine. This is in some cases more than enough to offset the lower $CO_2$ emission from LNG engines, as the $CO_2$ equivalent emission exceeds that of engines powered by fuel oil. Due to lack of regulation, there has not been any requirement to measure methane in the exhaust for certification, and thus methane slip is not included in the calculation of $CO_2$ equivalent emissions.

The methane slip is primarily a problem related to 4-stroke engines, which operate with premixed gas combustion. Methane trapped in small crevice volumes between piston and cylinder liner does not burn but escapes the cylinder without even burning in the exhaust. The slip was known to be large with the first engine generations but has since been reduced to levels below 1 %.

2-stroke engines using a low-pressure injection principle and a lean premixed combustion process (WinGD X-DF and MAN GA designs) can have methane slips comparable to or lower than new generation 4-stroke DF engines.

2-stroke engines from MAN ES using the high-pressure gas direct injection, ensures an almost complete combustion of the gas in a diffusion-controlled combustion process, like that used for diesel. These 2-stroke engines therefore have very low methane emissions.

Methane emissions have been documented by direct measurements, which clearly show the difference in emissions across engine technologies (Ushakov, S., Stenersen, D. & Einang, P.M. ). Finnish researchers provided a statistical study on methane emission levels in 2021, based on measurements from land on exhaust emissions from passing LNG powered ships (Grönholm, 2021). These studies have confirmed that the methane slip can be high with engines operating with low-pressure injection (premixed combustion type), while engines with high pressure direct injection have very low emissions of methane.

The International Council in Clean Transportation (ICCT) has studied the climate effect of using LNG as marine fuel, compared to MGO, VLSO and HFO (ICCT, 2020). The studies indicate that using LNG as fuel does not reduce the $CO_2$ equivalent emissions for any engine types, when upstream methane emissions and methane slip from engines are included. The $CO_2$ equivalent emissions are shown to be much higher for 4-stroke DF engines with low pressure port fuel injection, which are known to have the highest methane slip.

Methane is a very chemically stabile molecule, which is difficult to oxidize with common catalytic materials at normal exhaust temperatures. Noble metal catalysts such as platinum could provide an efficient conversion with sufficient exhaust temperature, but these are very sensitive to sulfur poisoning and will be deactivated in a short time by the sulfur from the pilot oil combustion.

Work on sulfur tolerant catalysts has been ongoing since the problems with methane slip were first acknowledged. Progress has been made with experimental catalyst materials that are more efficient at lower temperatures, and more resilient to sulfur poisoning (Peter Glarborg/Anker Degn). Companies specializing in catalysts, such as Haldor Topsøe, Umicore, BASF and other companies who specialize in catalysis, now offer novel catalyst coatings, which are more sulfur tolerant and more efficient in methane conversion. These products are, however, not in demand since there is currently no regulation on methane emissions from marine engines.

## Battery electric propulsion systems

With increasing focus on and ambitious targets for the $CO_2$ emissions in the marine sector, new fuel alternatives with lower carbon footprints are now being considered. These new fuels however require technologies, which are still in the early stages of development and demonstration for marine vessels.

The AFI provides an insight in the alternative fuels and propulsion technologies which are now being used in part to comply with IMO Tier III, fuel sulfur regulations and $CO_2$ reductions. Currently, ships with alternative fuels included in the AFI statistics include ships equipped with batteries as part of the propulsion and/or power systems, methanol, and hydrogen. Ammonia will be added to the database later this year.

### Battery powered ships

Batteries provide a clean energy source for propulsion and power, and pure electric vessels are by default compliant with all IMO emission regulations.

The AFI provides an insight to the application of batteries in ships, which covers both hybrid, plugin hybrid and pure electric. Data are provided and maintained by members of the Maritime Battery Forum.

According to AFI, almost 500 ships are currently operating with batteries, and an additional 157 ships are ordered. Of those currently in operation, 23 % (128 ships) are pure electric ships, meaning there is no support from combustion engine generators. 51 % (261 ships) are hybrid installations, in which case the battery installations are primarily used to increase efficiency by load shaving. Plug in hybrid accounts for 23 % (90 ships), with the plug-in addition meaning that the batteries are charged at port stay, which makes sense e.g. in ferry operation on fixed routes.

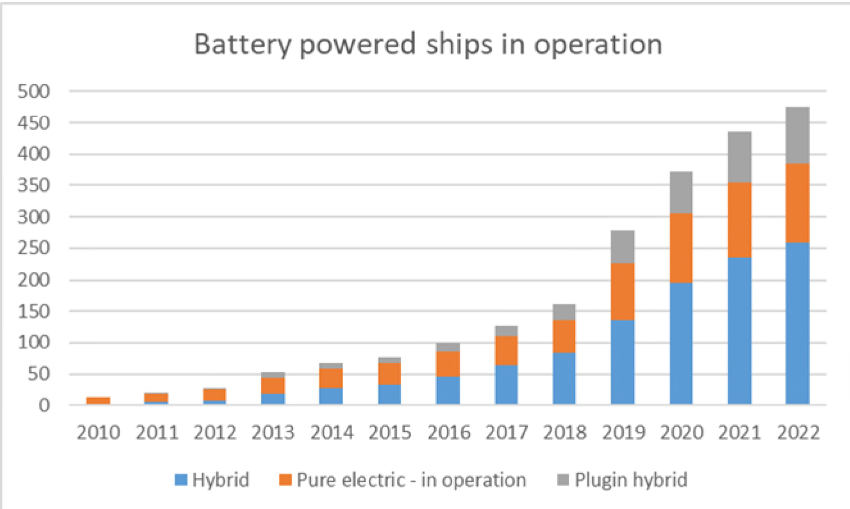


*Figure 82: Development in battery powered ships. Source: DNV AFI*

Figure 82 displays the development in battery powered ships for the last 21 years. Most ships are newbuilds, but 157 of the 495 in operation are retrofit projects, which to a large extend are hybridizations with the purpose of saving fuel.

Batteries are currently only feasible as a main propulsion solution on short distances. Most of the battery installations are found on car/passenger ferries (224 operating, 71 ordered), which often operate relatively short distances between destinations. On these routes, replacing decommissioned ships with new battery powered ships is becoming economically feasible.

The development of battery technology is however moving very fast, and electrification is a highly relevant topic in the marine sector (Craig, 2020). Several projects are currently in motion with the aim of demonstrating battery propulsion systems on even large ships. There are many indications that batteries and electrification will provide a large impact in short distance shipping within the next decade, as is currently the case with road transportation.

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