



Evaluation of Ethanol Use in Marine Shipping

Robert L. McCormick and Nimal Naser

National Laboratory of the Rockies

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Strategic Partnership Project Report
NLR/TP-2A00-101938
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National Laboratory of the Rockies
15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nlr.gov

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List of Acronyms

ANP	Brazilian National Agency of Petroleum, Natural Gas and Biofuels (fuels regulatory body)
ASTM	ASTM International (standards-setting body)
CEN	European Committee for Standardization
CO ₂	carbon dioxide
CO _{2eq}	carbon dioxide equivalent
ECA	Emission Control Area
GFI	Greenhouse gas fuel intensity
GHG	greenhouse gas
HFO	heavy fuel oil (also known as residual fuel oil)
IMPCA	International Methanol Producers and Consumers Association
IMO	International Maritime Organization
ISO	International Organization for Standardization
LHV	lower heating value
LNG	liquefied natural gas
MARPOL	International Convention for the Prevention of Pollution from Ships
MGO	marine gas oil (a fuel similar to diesel fuel)
MMA	Grade A marine methanol
MMB	Grade B marine methanol
MMC	Grade C marine methanol
mt	metric ton
NO _x	nitrogen oxides
NZF	Net-Zero Framework
PM	particulate matter
SO _x	sulfur oxides
TEU	twenty-foot equivalent unit
ULSD	ultra-low-sulfur diesel
VLSFO	very low sulfur fuel oil (HFO with less than 0.5 wt % sulfur)

Executive Summary

- Ethanol is clearly a viable fuel for ships, based on the introduction of methanol dual-fuel engines more than a decade ago.
 - Properties are very similar to those of methanol, such that methanol infrastructure and experience can accelerate ethanol adoption.
 - Ethanol has significant advantages over methanol, including 35% higher energy content, lower toxicity and corrosivity, and more rapid biodegradation if spilled into the ocean. Additionally, bioethanol is available today at scale and at a much lower price than biomethanol.
 - Large dual-fuel methanol engines can operate on ethanol with no changes. The approximately 112 to 120 methanol dual-fuel ships in operation today could consume 6 million metric tons (mt) or 2 billion gallons of ethanol annually if operated full time on this fuel.
 - Several trial voyages were conducted using ethanol in late 2025 and 2026. In the summer of 2026, commercial ship-to-ship bunkering of ethanol was initiated.
- The global market for fuels in marine shipping is massive, with an estimated 259 million mt (86 billion gallons assuming 330 gal/mt for heavy fuel oil) consumed in 2023.
- A significant driver for the use of alternative fuels in shipping, including ethanol, is the International Maritime Organization's Net-Zero Framework. This framework recognizes 170 different fuel pathways, including 3 ethanol pathways. Regional regulations such as Fuel EU Maritime are also significant drivers.
- An International Organization for Standardization (ISO) standard for ethanol to be used in shipping is needed. ISO has already initiated work on this standard. U.S. ethanol industry participation is critical to ensure that the standard is based on modern scientific information on corn ethanol.
- A key uncertainty is an assessment of needed supply chain infrastructure development, supply chain volatility, and costs:
 - What infrastructure is needed to supply ethanol at key U.S. and international ports?
 - What are key U.S. ports for ethanol bunkering?

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Introduction

Roughly 80% of global trade occurs via marine shipping, primarily utilizing heavy fuel oil (HFO) or very low sulfur fuel oil (VLSFO) [1]. Marine shipping is by far the most efficient and lowest-cost approach to moving cargo. In part, this efficiency is achieved because of the huge scale in modern shipping, with the largest container ships capable of carrying more than 20,000 twenty-foot equivalent units (TEU; a single 20-foot-long container) [2]. These can carry up to 5 million gallons (16,000 metric tons [mt]¹) of HFO for propulsion of the ship [3].

Marine shipping is regulated by the International Maritime Organization (IMO), a United Nations agency charged with maritime safety, security, and prevention of marine pollution from ships; reducing air pollutant emissions such as sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM, or soot) [4]; reducing the impact of fuel spills on the environment; and potentially in the future reducing greenhouse gas (GHG) emissions [5].

A potentially low-cost approach to meeting all these objectives is to switch from conventional HFO to cleaner biofuels. For example, biodiesel is approved for use as B100 in many ships [6] and in the International Organization for Standardization (ISO) 8217:2024 standard for marine diesel and residual fuels. Additionally, methanol and ethanol are approved for use in vessels modified or built specifically to handle, store, and burn them [7, 8, 9]. This document provides a summary of U.S. ethanol production and uses, reviews information on the use of ethanol in shipping, and summarizes remaining challenges and barriers.

IMO estimates that shipping overall consumed 4.2 million barrels per day or 64 billion gallons (211 million mt) of fuel per year in 2023 [10]. However, this number is for international shipping, and ships greater than 5,000-mt gross weight, that are required to report fuel use to IMO. This number is underreported in that only 28,620 ships out of 35,143 (81.4%) provided data to IMO in 2023. Extrapolation to full reporting suggests a total of 259 million mt (86 billion gallons). Other estimates place the total at more than 300 million mt annually because the IMO estimate does not include smaller ships or domestic shipping [11].

Accounting for the large difference in energy content between HFO and ethanol, in the extreme case of all ships running on ethanol (less 5% for liquefied natural gas [LNG] ships and less 5% for diesel/fuel oil pilot to ignite the ethanol), the 259-million-mt market would be as large as 355 million mt of ethanol (118 billion gallons). While this extreme case is not likely to be possible, clearly the marine market represents a huge opportunity for ethanol.

¹ Fuel quantities are typically discussed in metric tons for shipping; 335 gallons of ethanol weighs 1 mt.

IMO Net-Zero Framework

The IMO Net-Zero Framework (NZF) is based on IMO's 2023 GHG strategy, which was adopted by the Marine Environment Protection Committee (MEPC.377(80)) [12]. Targets include reducing carbon intensity by at least 40% by 2030 against a 2008 baseline, decreasing total annual GHG emissions by no less than 20% by 2030 and 70% by 2040, and achieving net zero for total emissions by around 2050. The strategy requires at least 5% of energy used in shipping to be supplied by zero- or near-zero-GHG technology or fuel by 2030.

The framework includes a global fuel standard that gradually reduces how much GHG is emitted for each unit of energy used on a life cycle basis, a pricing mechanism allowing ship owners to earn credit if they exceed the GHG emission limits, and purchase credits if they fail to meet the requirements [5]. To be used for compliance with the IMO NZF, fuel life cycle emissions must be verified using procedures recognized by IMO's Marine Environmental Protection Committee [13, 14].

Ship emissions are quantified in terms of GHG fuel intensity (GFI), a measure of GHG emissions per unit of energy that is very similar to what has been called carbon intensity in other contexts. It has units of grams of carbon dioxide equivalent ($\text{CO}_{2\text{eq}}$) per megajoule, where $\text{CO}_{2\text{eq}}$ means that it includes methane and nitrous oxide emissions. A zero- or near-zero-emissions fuel is defined as having a GFI of no more than $19.0 \text{ gCO}_{2\text{eq}}/\text{MJ}$ —80% lower than the current average of $93.3 \text{ gCO}_{2\text{eq}}/\text{MJ}$. The NZF is a primary driver for increased use of lower-GFI fuels such as ethanol, along with regional regulations such as Fuel EU Maritime. Notably, there may be some adoption of alternative fuels in harbor craft and inland marine vessels to reduce air pollutant emissions such as SO_x , NO_x , and PM.

These regulations would apply to international shipping and ships greater than 5,000 mt gross weight. These ships are believed to emit 85% of GHGs emitted by marine shipping. As with all IMO regulations, the NZF would be enforced by the 176 IMO member states.

For a fuel to be considered in the IMO NZF, it must have a GFI calculated from well-to-wake life cycle analysis using IMO-approved methodology [14]. There are currently 170 pathways that IMO is considering for default the GFI, including 3 ethanol pathways.

Ethanol Background

Ethanol, also known as ethyl alcohol, is produced from biomass and used for various purposes in transportation, chemical, and pharmaceutical industries. It is produced by fermentation of sugar, which can be derived from starch or cellulose. In the United States, ethanol is mostly produced from corn starch. Ethanol has a long history as a fuel component. For example, the original Ford Model T, produced in 1908, was a flexible-fuel vehicle with carburetors that could be adjusted to use ethanol, gasoline, or a mixture of the two [15]. More recently, the energy crisis of the 1970s led to the introduction of gasoline with 10 vol % ethanol, and legislation exempted ethanol blends from part of the federal highway tax. The phaseout of tetraethyl lead in gasoline during the 1980s generated interest in the use of ethanol as a high-octane blendstock. In the 1990s, oxygenates, including ethanol, were mandated in gasoline to reduce carbon monoxide and volatile organic compound emissions. However, methyl tert-butyl ether dominated the oxygenate market until it was phased out beginning in March 2000 [16]. Since that time, ethanol blending has grown to the point where more than 95% of gasoline consumed in the United States contains 10% ethanol [17]. In January 2011, the U.S. Environmental Protection Agency approved the use of E15 in 2001 and newer model year automobiles [18], and use of E15 is becoming more common [19, 20].

Global fuel ethanol production exceeded 31 billion gallons (117 billion liters, or 93 million mt) in 2024 [21] and is forecast to exceed 140 million mt by 2034 [22]. The United States was the largest producer at 16 billion gallons, with Brazil in second place at 9 billion gallons. India, the European Union, and China each produced more than 1 billion gallons.

The United States has about 2 billion gallons per year of idled production capacity (nearly 6 million mt). Ethanol is primarily manufactured in the Midwestern United States and transported nationwide by rail, commonly as unit trains of $100 \times 30,000$ -gal ethanol tank cars (approximately 9,000 mt). About 1.8 billion gallons were exported in the marketing year from September 2023 to August 2024, and more than 2.1 billion gallons in 2025. Canada, the European Union, India, and the United Kingdom are the largest destinations [23]. Exports by ship were predominantly from the Houston area. The United States imports very little ethanol; for example, only 4 million gallons were imported in 2024, primarily from Brazil [24]. Brazil exports around 700 million gallons (2.6 billion liters) of ethanol annually, with South Korea and the Netherlands as major customers [25].

A 2021 review examined many studies of the carbon intensity of corn ethanol in the United States, highlighting several factors that have changed over time [26]. The study found that market factors had led to reduced fertilizer and diesel fuel use on farms and more efficient use of energy in ethanol plants and presented a state-of-the-art assessment of land use change effects. The study concluded that a best estimate of ethanol carbon intensity is $51.4 \text{ gCO}_{2\text{eq}}/\text{MJ}$ —46% lower than for petroleum fuels. The largest component was CO_2 from ethanol production, where about one-third of the carbon in feedstock sugar is converted to CO_2 . Ethanol producers are increasingly adopting sequestration of CO_2 , which qualifies for a recently enacted tax credit. Sequestration may reduce carbon intensity by as much as $30 \text{ gCO}_{2\text{eq}}/\text{MJ}$ [27].

Table 1 shows the physical properties of ethanol. Most notable for the marine shipping context is the lower heating value (LHV) of ethanol of 26.9 MJ/kg, which is significantly lower than

marine gas oil (MGO) or HFO, which are greater than 40 MJ/kg. Also notable is the flash point of 14°C, necessitating nitrogen blanketing of the fuel tanks [9]. A useful number is that 335 gallons of ethanol at 15°C weighs 1 mt.

Table 1. Physical Properties of Pure Ethanol

Property	Ethanol
Boiling point, °C ^a	78.4
Freeze point, °C ^a	-114
Density at 15°C, kg/m ³ ^b	793.5
Kinematic viscosity at 20°C, mm ² /s	1.36 ^c
LHV, MJ/kg (specific energy)	26.9 ^d
LHV, MJ/L (energy density)	21.4
Heat of vaporization at 25°C, kJ/kg ^a	918
Flash point, °C by closed cup method	14 ^e

^a NIST webbook [28]; ^b Measurement Canada [29]; ^c Engineering Toolbox; ^d Christensen et al. [30]; ^e Sigma-Aldrich, Safety Data Sheet for Ethyl alcohol, pure. Product Number: E7023.

Current Status of Marine Fuel Usage and Regulations

Conventional and Alternative Marine Fuels

IMO estimates total consumption of all fuels for international shipping in 2023 was 211–259 million mt, or approximately 65–80 billion gallons (5,000 mt gross weight and larger vessels) [10]. Other sources suggest this number is much higher at more than 300 million mt for all shipping, but these additional ships are not subject to IMO regulation [11].

As shown in Figure 1, since 2020 more than half the fuel used has been HFO, with an increasing proportion of light fuel oil brought about by the reduction of allowable sulfur content from 3.5 wt % to 0.5 wt % beginning in 2020 (although 3.5% sulfur fuel can be used if the ship is equipped with a SO_x scrubber, which is very common for large container ships). HFO is also known as residual fuel oil because it is the material that does not boil off during the distillation of crude oil. Property limits are described in ISO 8217:2024. It can have very high viscosity, up to 500 mm²/s at 50°C for the heaviest grade. Room temperature viscosity may be as high as 10,000 mm²/s, and this material has been described as a semisolid tar. This very tarry substance must be heated on board the ship to reduce its viscosity for it to be pumpable before injection into the engine. Light fuel oil is also a residual fuel but has a lower viscosity and may have lower sulfur content. MGO is a distillate fuel that is similar to diesel fuel.

Figure 2 shows that bulk carriers, container ships, and tankers consume most of the marine fuel. The largest alternative fuel used was LNG, and the primary ships that use LNG are LNG carriers—in many cases fueled in part by the LNG cargo boiloff. Very small amounts of other alternative fuels were used in the 2021 to 2023 period, as shown in Figure 3. Biofuel in this figure likely comprises primarily biodiesel and renewable diesel. In 2023, IMO reports that 4,000 mt of ethanol was used to fuel large bulk carriers, but little additional information appears to be available [10]. The fuels shown in Figure 3 represented less than 0.5% of fuel used in shipping in this time frame, but it is likely that use of LNG and methanol has increased significantly since 2023. As of the end of 2025 LNG remained the most widely adopted alternative fuel in marine shipping, with about 10% of the global fleet (in service and on order) by deadweight tonnage [31]. Methanol-capable ships are the second largest category after LNG, with a total of 112–120 vessels in operation, including 38 new deliveries in 2026 [32]. Approximately one-third of these vessels are methanol carriers, and one-half are container ships. A further 700 ships are methanol ready (purpose built for later conversion to methanol dual-fuel), and 300–350 are on order.

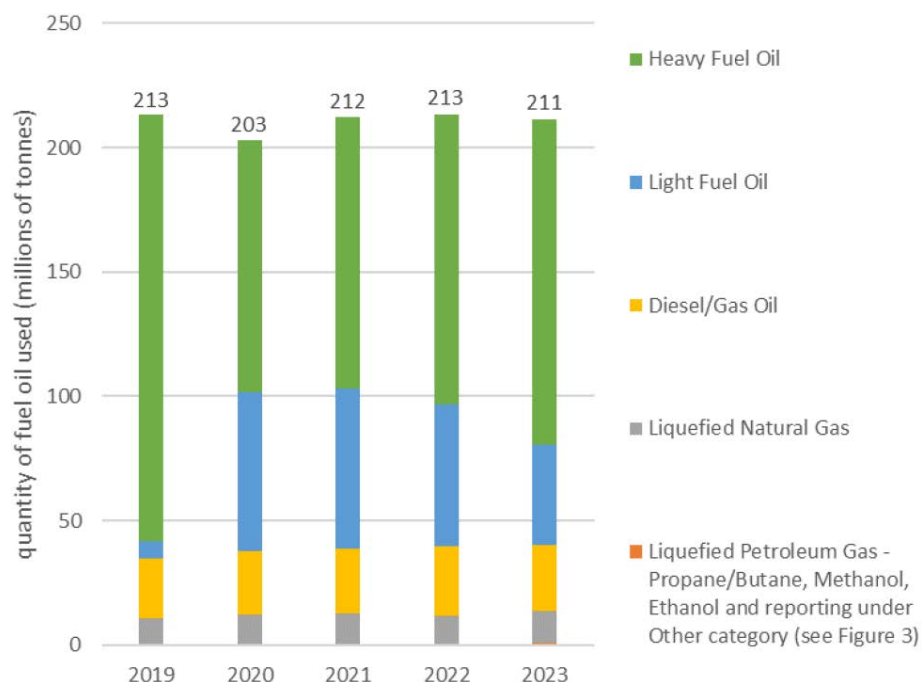


Figure 1. Aggregated annual amount of each type of fuel reported to IMO for 2019 to 2023. Chart reproduced from [10].

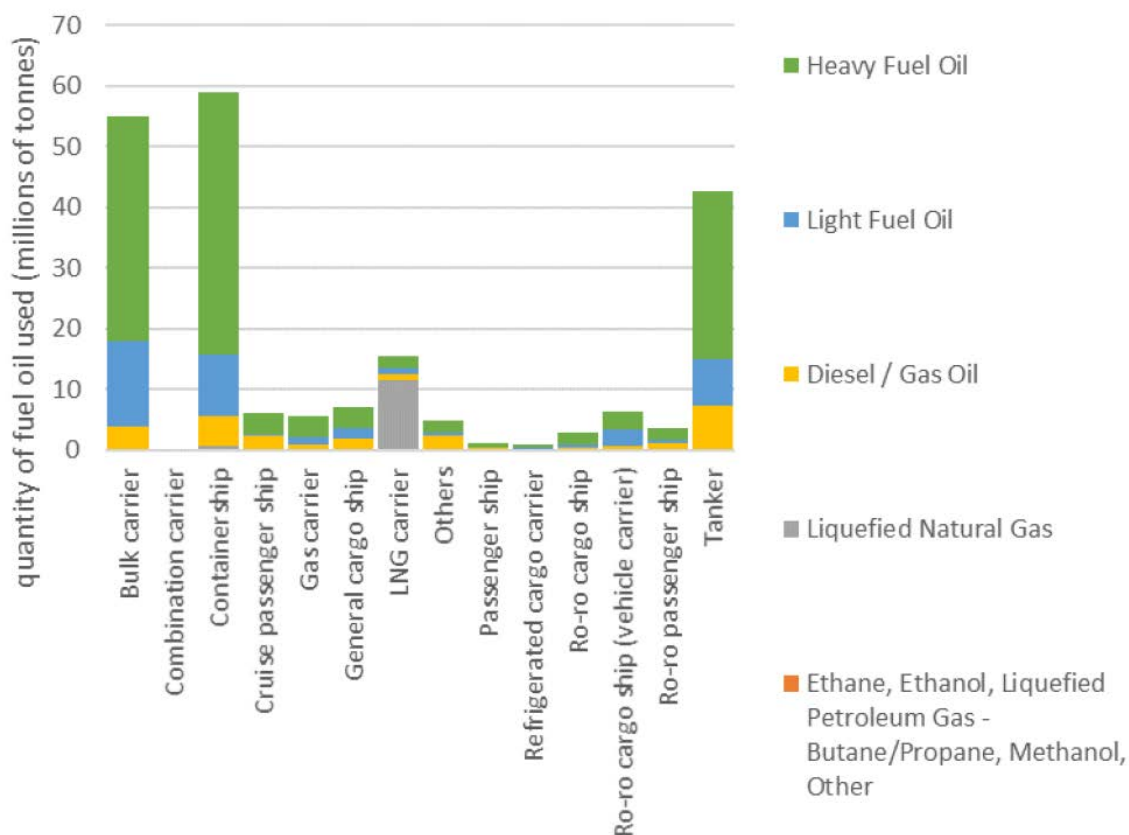


Figure 2. Annual amount of each type of fuel oil consumed and reported to IMO for ships of 5,000 gross tons and above by ship type for the 2022 reporting period. Chart reproduced from [10].

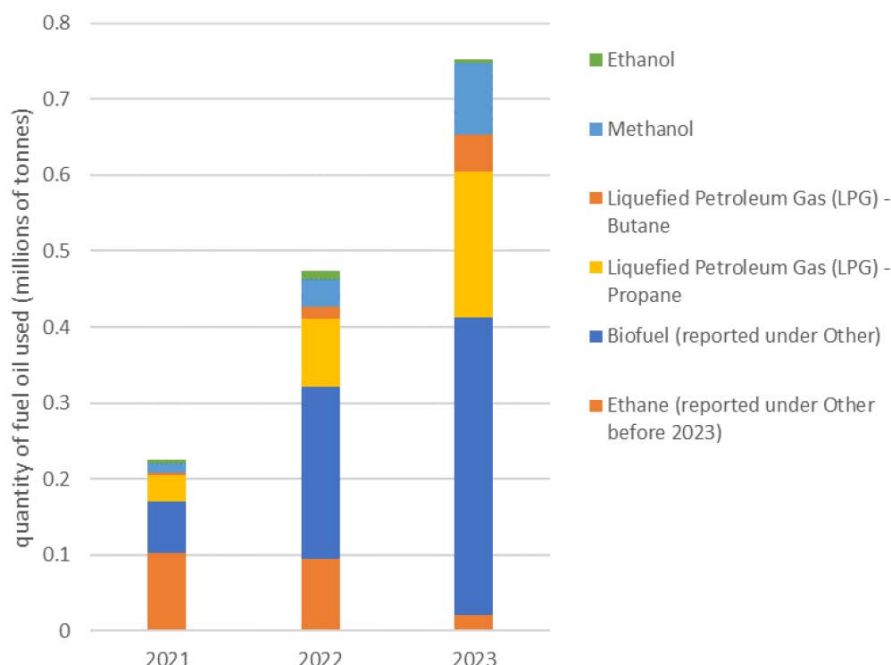


Figure 3. Aggregated annual amount of liquefied petroleum gas, ethane, ethanol, methanol, and biofuel consumed and reported to IMO from 2021 to 2023. Chart reproduced from [10].

Bunkering

Ship crews carefully monitor the amount of fuel on board using a combination of automated tank sounding gauges, pressure sensors, and flow meters. In modern ships the crew can track the weight of fuel in each tank in real time. This is especially critical before taking on board additional fuel (bunkering) to ensure that there is no spillage or overflow.

Bunkering is the process of supplying fuel to ships, which is typically brought to the ship by a bunker barge (ship-to-ship transfer), but can also be accomplished via pipe or hose from a land-based terminal or from trucks. Because of the large tonnages involved, as well as safety, environmental, and financial risk, ship bunkering is a complex and meticulously planned and regulated operation. Because alternative fuels such as methanol, ethanol, and LNG have significantly different properties than conventional fuels, bunkering procedures are also different, and these operations require the use of bunker barges designed specifically for handling these fuels.

The largest tonnage bunkering port is Singapore at 56.2 million mt in 2025—as much as 25% of bunker fuel used globally [33, 34]. All other ports have much smaller totals, with Rotterdam in second place at 9.8 million mt. Total bunkering tonnage for all ports in the United States is estimated at 18 million mt annually [35]. This is consistent with U.S. residual fuel oil production of around 18 million mt annually, as shown in Figure 4. To identify U.S. ports where bunkering is likely to occur, we can look at rankings for cargo tonnage, which show that Houston is the largest U.S. port overall, followed by several other ports on the U.S. Gulf Coast. Aside from methanol carriers, container ships are the most likely to be using methanol (or ethanol) in the near term, and the Port of New York and New Jersey is the largest container port, followed by Los Angeles, Long Beach, Savannah, and Houston [36].

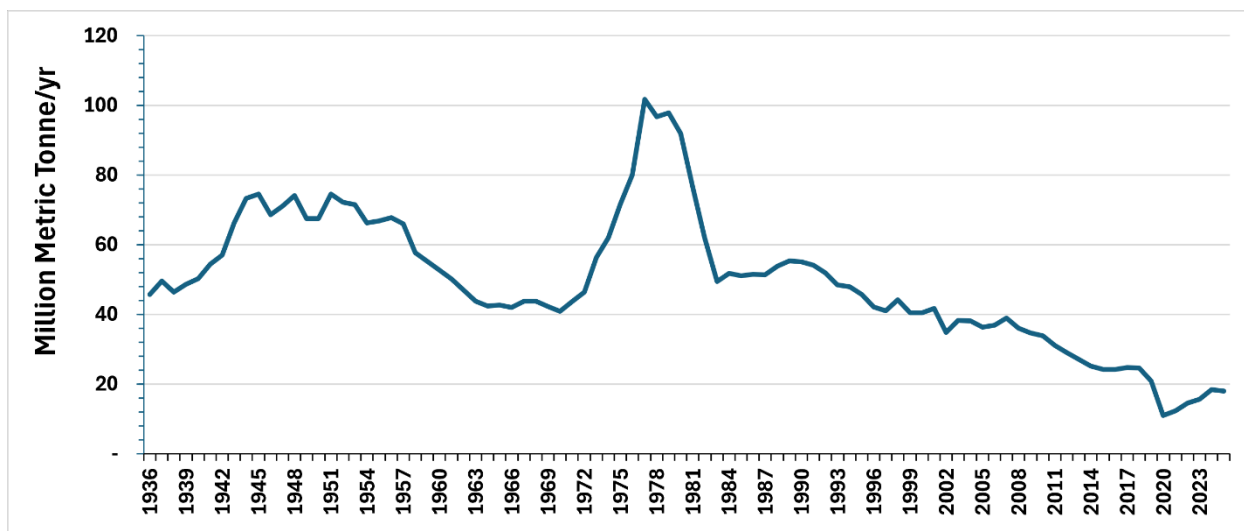


Figure 4. U.S. refinery and blender net annual production of residual fuel oil [37].

Air Pollutant Emissions

Regulations

The International Convention for the Prevention of Pollution from Ships (MARPOL) was adopted by the IMO and sets international standards for preventing ship-source pollution. Annex VI of MARPOL specifically addresses air pollution, which includes NO_x [38], SO_x, PM [39], volatile organic compounds [40], and ozone-depleting emissions [41]. It sets standards for vessel and engine manufacture, certification, and operation, along with standards for fuel quality. These standards are for implementation worldwide, while stricter standards apply for Emission Control Areas (ECAs). An ECA is a body of water designated by IMO where ships must follow stricter emissions regulations for SO_x, PM, NO_x, or all three. Current ECAs include the Baltic Sea, North Sea, Mediterranean Sea, and the North American ECA that includes the entire coast of the United States and much of Canada. Annex VI sets the following requirements:

1. NO_x emission standards apply for marine diesel engines above 130 kW of power. The requirements are for both main propulsion engines and auxiliary engines with NO_x emission levels as specified in Table 2 and Figure 5.
 - A. Tier I and Tier II limits apply worldwide. Tier II standards can generally be achieved by optimization of the engine combustion process. Changes in parameters such as fuel injection timing, pressure, rate (rate shaping), fuel nozzle flow area, exhaust valve timing, and cylinder compression volume allow engine operation to comply with these regulations.
 - B. Tier III limits apply only in ECAs. Tier III standards typically necessitate the use of advanced NO_x control technology. These may include measures like water injection into the combustion process (via fuel, scavenging air, or directly into the cylinder), exhaust gas recirculation, or selective catalytic reduction systems. For the large two-stroke engines powering the largest ships and consuming most maritime fuels, main engine maximum speed (*N*) will be less than 130 rpm.

Table 2. NO_x Emission Limits in MARPOL Annex VI [38]

Tier	Date	NO _x Limit, g/kWh for different max. engine speed (<i>N</i>) in rpm		
		<i>N</i> < 130 130 ≤ <i>N</i> < 2,000 <i>N</i> ≥ 2,000		
		<i>N</i> < 130	130 ≤ <i>N</i> < 2,000	<i>N</i> ≥ 2,000
Tier I	2000	17.0	$45 \times N^{-0.20}$	9.8
Tier II	2011	14.4	$44 \times N^{-0.23}$	7.7
Tier III	2016	3.4	$9 \times N^{-0.20}$	1.96

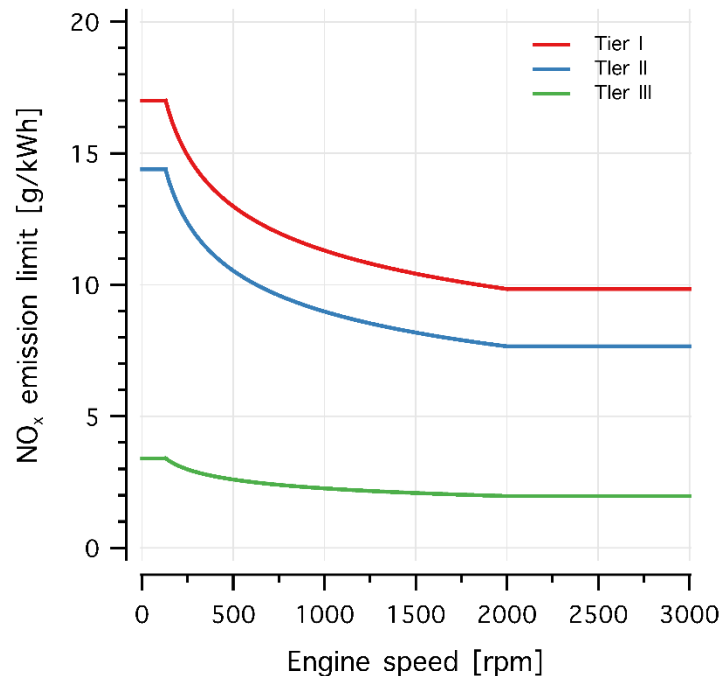


Figure 5. NO_x emission limits in MARPOL Annex VI for various engine speeds [38].

2. Sulfur content limitations in marine fuels are intended to restrict SO_x emissions from shipping. SO_x and PM emission controls apply to all fuel oils and all combustion equipment on board. This includes main and auxiliary engines, boilers, and inert gas generators. Compliance is achieved primarily by restricting the maximum sulfur content of fuel oils. The current fuel sulfur limits are 0.5 wt % for operation outside of an ECA (known as VLSFO) and 0.1 wt % for operation inside an ECA. Both methanol and ethanol contain almost zero sulfur, far below these limits. Ships can also operate on higher sulfur fuel and employ SO_x scrubbers.

Fuel Spillage

The International Convention on Civil Liability for Bunker Oil Pollution Damage (2001) is the main instrument covering spills of fuel from all seagoing vessels. It established a system of strict liability for shipowners for pollution damage, including environmental damage, and requires ships over 1,000 gross tons to maintain compulsory insurance.

When HFO is spilled into the sea, there can be large environmental impacts, as it can form a thick film on the surface that spreads slowly due to its high viscosity. Depending on the density,

HFO might float on the surface or be suspended under the surface if the density is greater than 1 g/mL. Further, because of its slow evaporation rate, most of the HFO remains in the environment for extended periods of time. HFO readily forms stable emulsions of oil in water and water in oil that are resistant to natural breakdown and difficult to recover. Slow oxidation of HFOs can also occur, leading to changes in properties such as viscosity, density, and pour point [42, 43]. If spills are not properly contained, the impact on coastlines can be high. Cleanup for even a small spill can cost millions of dollars. HFO contains compounds such as polycyclic aromatic hydrocarbons, which are harmful to aquatic organisms and bioaccumulate in the food chain.

Spilling MGO in marine environments differs from HFOs, primarily due to its lower density and higher volatility. Gas oil is considerably less viscous, allowing it to quickly spread on the water surface when it is released. Unlike HFO, MGO contains a high concentration of volatile hydrocarbons that lead to extensive evaporation, such that the MGO can evaporate within the first 24–48 hours of release, especially with warm and windy weather. This evaporation reduces the amount of oil remaining on the surface, but volatile organic compounds that are toxic can impact marine organisms and create related inhalation risks to response operators. MGO also disperses more easily into the water, and with the assistance of chemical dispersants, biodegradation can be enhanced, but there may be a risk of short-term aquatic toxicity. MGO does not emulsify as easily or stably as HFO. However, due to its solubility and toxicity, MGO poses acute environmental risks for marine organisms and coastal environments. It has low persistence in seawater compared to HFO, but the initial impact can be extreme. Shore pollution is less common and less problematic to remove.

Marine Engines

Large Two-Stroke Engines

Large commercial ship engines are low-speed (100–300 rpm) two-stroke engines owing to their higher efficiency, higher torque at low speeds, and ability to burn low-cost heavy fuels. Compared to on-land diesel engines that are four-stroke engines delivering power in every two revolutions, marine engines produce power in every revolution (i.e., two strokes), with scavenging (the process of replacing exhaust with fresh intake mixture), compression, combustion, and exhaust occurring in one revolution. Two-stroke engines provide a higher power-to-weight ratio compared to four-stroke engines. Low-speed two-stroke marine diesel engines are highly efficient, with peak thermal efficiency greater than 50%. Fuel consumption can be as low as 160–170 g/kWh with design based on very long periods of steady operation on HFO. Output powers range from 1,100 kW to more than 97,000 kW, enabling them to power the biggest commercial vessels.

The low rotational speed of these engines allows direct mechanical coupling between the propeller shaft and the crankshaft without the need for reduction gearing (i.e., a transmission). The absence of a complicated gear system also increases the power-to-weight ratio and reduces mechanical complexity and production cost. In addition, the two-stroke layout is mechanically simpler because intake valves are not used, which reduces the number of components prone to mechanical failure. Instead, the cylinder liner has inlet ports located about two-thirds of the way down from the top that are opened and closed by the piston motion.

Marine engines for commercial vessels can be 10 to 15 meters tall to accommodate the large pistons and crankshafts needed for propelling ships. Two-stroke diesel engines require forced induction (turbocharging and/or supercharging) for air charging as well as scavenging of the cylinder.

The operating cycle can be described as commencing from the bottom dead center of the piston. As the piston rises, it covers and closes the inlet ports and compresses the trapped air, with compression ratios in the range of 17:1 to 23:1, and pressures on the order of 40 bar at the end of the compression stroke (first stroke). Fuel is directly injected through several injectors in the cylinder head at 10 to 20 crank angle degrees before the top of the compression stroke. Due to the high temperature of the compressed air, the injected fuel autoignites and burns as a spray. This results in rising cylinder pressure, which typically peaks in the range of 180 to 195 bar. This pressure pushes the piston down in the power stroke (second stroke), and work is transmitted through the connecting rod through the crosshead bearing to the crankshaft, converting linear motion into rotational energy. As the piston continues down, it uncovers the inlet ports, allowing air into the cylinder at pressures of 30–70 kPa above ambient (about 1.3–1.7-atm absolute pressure), and the exhaust valve is opened. Air flow pushes the exhaust gases out. At the bottom of the power stroke, the piston starts its upward stroke—covering the inlet ports and beginning a new compression process.

Smaller Four-Stroke Engines

Medium and small marine vessels that include ships, boats, ferries, and tugs usually operate with four-stroke diesel engines. Auxiliary engines used for power generation on larger ships may also

be four-stroke. Diesel engines are typically used as they are efficient, durable, and are able to provide reliable torque during variable operating conditions. These smaller vessels usually burn MGO or ultra-low-sulfur diesel (ULSD), as opposed to the HFO or VLSFO burned by most large oceangoing commercial vessels. MGO is a refined distillate fuel similar to land-based diesel but formulated for use in marine applications and has higher fuel density. It has a much lower sulfur content than traditional marine fuels and therefore allows vessels to meet the strict international emission standards, especially for operation in ECAs. ULSD is a fuel that contains sulfur levels typically below 15 ppm. It is widely available because it is used in both on-road and off-road land-based diesel engines and thus can be easily obtained by small vessels refueling in ports shared between marine and land-based customers. ULSD is compatible with modern emission control technologies, including diesel particulate filters and selective catalytic reduction systems. There are a few operational advantages with the use of MGO or ULSD in marine diesel engines. However, MGO and ULSD have a higher cost per ton than HFO, requiring maximizing engine efficiency for economic purposes.

Dual-Fuel Engines

Dual-fuel two-stroke engines have emerged as an important engine technology in the marine sector for burning low-cetane-number alternative fuels while maintaining the high power-density and reliability required for long-haul transport. These engines have the capability to operate in two modes: one on conventional HFO or MGO, and a second where HFO or MGO is used as a pilot to ignite a low-cetane-number fuel such as LNG, methanol, or ethanol. The flexibility to operate on either conventional or alternative fuels is considered a major advantage by shipping companies as they strive to ensure the relevance of these long-lived, high-cost assets in an uncertain regulatory environment.

Marine engine manufacturers have advanced dual-fuel concepts to a mature, widely adopted technology spanning ultra-large container vessels, tankers, and bulk carriers, as well as smaller ships. Figure 6 shows a diagram of injector layout (similar diagrams have been presented by equipment manufacturers) [44]. When air enters the cylinder, it creates a swirling flow field. There are typically two or three sets of pilot and low-cetane-number fuel injectors, with the pilot located upstream of the primary fuel relative to the swirling air motion. This air motion pushes the burning pilot spray into the primary fuel jet, causing it to ignite and burn as a spray.

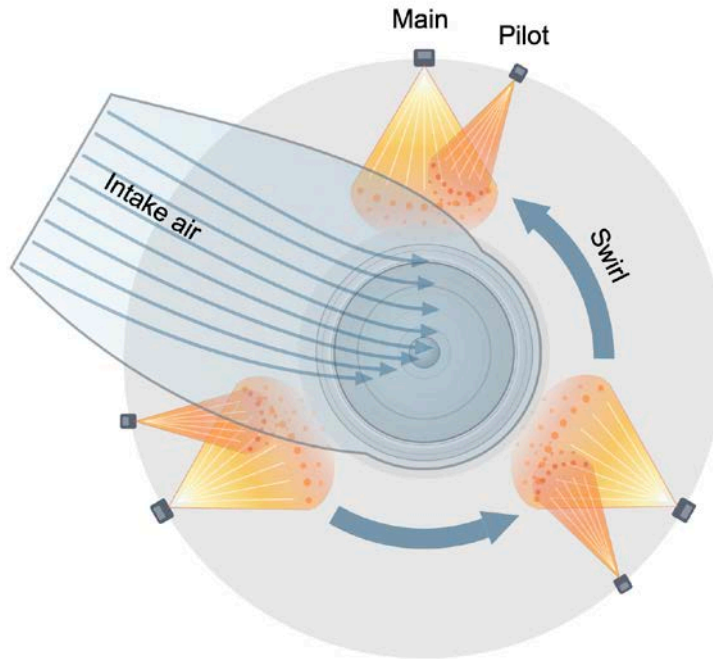


Figure 6. Pilot and primary fuel injector layout for dual-fuel engines (graphic by N. Naser, NLR).

LNG dual-fuel engines are the most widely deployed dual-fuel engines and use a lean burn strategy in which vaporized natural gas is injected into the cylinder and ignited by a small quantity of pilot liquid fuel (MGO or HFO) injected at high pressure, maintaining a diesel-like compression-ignition process but with LNG as the main energy carrier. The pilot fuel fraction is usually in the order of 1%–5% of the total energy input, which is sufficient to ensure stable ignition and combustion over a wide load range. When LNG is unavailable [45], or under certain operating conditions such as low-load, transient maneuvers, the same engine can be operated with the conventional liquid fuel alone without hardware changes, providing operational flexibility and redundancy. This is achieved by advanced engine management systems, including in-cylinder pressure measurement-based control, that control pilot injection timing, and air management to avoid misfiring and other engine combustion issues while maintaining target power output and speed. For LNG, SO_x is eliminated due to the very low sulfur content in natural gas, and PM emissions are low due to the absence of heavy aromatics. NO_x reductions of 85%–90% compared with conventional HFO engines are possible, although these engines require additional NO_x abatement to meet Tier III emissions requirements.

Methanol dual-fuel engines, like the Everllence ME-LGIM [46], the WinGD X-DF-M [47], and those from Wartsila [48] and Caterpillar [49], can use either methanol or conventional marine fuels while employing the same diesel engine design. For methanol operation, a small amount of pilot fuel (1%–5% of total energy input) is injected to initiate combustion [50]. Methanol is injected at high pressure for better spray atomization, and after injection it burns as a spray.

Methanol in Marine Shipping

Methanol is a widely used chemical and solvent with production of 92.8 million mt (34 billion gallons) worldwide in 2024. By 2030 production is projected to grow to 116.3 million tons [51]. Methanol is a commodity that is shipped as cargo all over the world, with 35% of production exported in 2023 [52]. While methanol is almost entirely made from natural gas, it can be made from many feedstocks including coal, biomass, and waste CO₂. Depending on how it is produced, methanol can be assigned a color name:

- Green methanol is made from biomass or captured CO₂ and green hydrogen (made by water electrolysis using renewable electricity).
- Blue methanol is made using captured CO₂ and blue hydrogen (made from natural gas by steam methane reforming with capture and sequestration of CO₂).
- Gray methanol is made from natural gas.
- Brown methanol is made from coal.

Almost all methanol produced today is gray methanol.

Methanol is approved as a marine fuel in the sense that IMO has published interim guidelines on safety requirements for use of methanol and ethanol, including fuel system design, ventilation, leak detection, and firefighting [9]. These interim guidelines are being integrated into the mandatory International Convention for the Safety of Life at Sea section entitled “International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels” [53]. There are a total of 112 to 120 methanol-capable vessels in operation, including 38 new deliveries in 2026 [32]. A further 700 are methanol ready (purpose built for later conversion to methanol dual-fuel), and 300 to 350 are on order. The first orders were for methanol-carrying tankers, but today most methanol-capable ships on order are ultra-large container ships (>14,500 TEU) and new Panamax container ships (10,000 to 14,500 TEU)—highlighting the strong interest in the container shipping sector in alcohol fuels [54]. Methanol-capable ships have undergone significant development since their first introduction [55]. All of these vessels are capable of operating on conventional fuel oil or methanol (in dual-fuel mode with MGO or HFO as a pilot ignition source) and today operate primarily on conventional fuel oil.²

Methanol has several advantages over conventional marine fuels for large commercial vessels. Methanol is essentially sulfur-free, so that SO_x emissions are effectively eliminated. As an oxygenate it produces very low soot emissions and burns cooler, reducing NO_x, although additional reduction is required to meet IMO Tier III limits [56, 57, 58]. For example, Everllence reports a 30%–50% NO_x reduction relative to MGO for their ME-LGIM engine [59]. In the event of a large methanol spill, the fuel would quickly dissolve and be rapidly dispersed and biodegraded, in contrast to the high-cost negative impacts of a large HFO spill [60, 61].

Basic properties of neat methanol are shown in Table 3 and compared to properties of MGO. For methanol, the boiling point is much lower, but it is a liquid, making storage and handling similar to that of conventional fuels. Flash point is 11°C, indicating that a flammable mixture could exist

² It is important to stress that for methanol dual-fuel engines methanol and fuel oil are not blended, as methanol is insoluble in fuel oil. They are stored in separate tanks and injected into the engine separately, as described in Figure 6.

in tank ullage, necessitating inert gas blanketing on board the ship and bunkering vessel and demanding better fire detection and ventilation on ships [9]. This tank headspace purging may also limit water uptake from humid air [62]. Both specific energy and energy density are less than half of the values for MGO, while mass density is 10% lower. The lower energy density means that 2.4 times more volume of methanol than diesel or MGO fuel is required to achieve the same vessel range [50].

Table 3. Properties of Methanol and MGO

Property	Units	Methanol	MGO
Boiling point or T90	°C	64.6 ^a	--
Flash point	°C	11 ^a	>60 ^c
Net heat of combustion (specific energy)	MJ/kg	20.0 ^b	43 ^d
Net heat of combustion (energy density at 15°C)	MJ/L	15.9	38
Density at 15°C	kg/m ³	796.1 ^a	<890 ^c
Kinematic viscosity at 20°C	mm ² /s	0.75 ^e	2 – 6 ^c

^a From ISO 6583:2024.

^b Value from NIST webbook.

^c DMA grade in ISO 8217:2024.

^d Typical value from [63].

^e Engineering Toolbox

Methanol is toxic to humans and can be taken into the body by inhalation, ingestion, or skin or eye contact. Care must be taken to prevent exposure to those handling the fuel as well as ship crews. Because of methanol's different corrosion properties than conventional fuel oil, the compatibility of tank coatings, piping, seals, and other components must be carefully considered.

Today, methanol is produced primarily for use as a chemical and meets the International Methanol Producers and Consumers Association (IMPCA) specifications that describe the purity and properties for use to make multiple products [64]. The main requirements of the IMPCA specification are shown in Table 4. This specification was used as the starting point for the development of ISO 6583:2024 “Methanol as a fuel for marine applications – General requirements and specifications.” The requirements for the three grades in this specification are also shown in Table 4. Several of the IMPCA requirements that are not relevant for marine use are not included in the ISO standards. The various grades of ISO 6583:2024 ensure that the methanol is primarily methanol, with minimal contaminants including ethanol, acetone, sulfur, chloride, and acids. The MMA grade is primarily the same as IMPCA but allows buyers and sellers to agree on limits for lubricity and particle count that are important for fuel injector durability in high-speed four-stroke engines. MMB grade is the same as MMA but has no requirements for lubricity and particle count. The MMC grade has the same requirements as MMB but wider tolerance for many of the properties listed. The strict limits on ethanol content in ISO 6583:2024 do not appear to have a technical justification, as even several weight percent ethanol (or higher) should have no impact on fuel performance properties or combustion.

Methanol is available in more than 120 ports globally [65], although only about 48 ports offer commercial methanol bunkering as of June 2026 [66]. Thus, fuel bunkering infrastructure is lagging behind ship development, and most methanol-capable ships are operating on HFO [54]. Methanol bunkering requires a dedicated barge or methanol tanker. As of 2025, there were 12 dedicated methanol bunker barges worldwide, with most in Singapore [54]. Shipboard bunkering stations have been designed to be compatible with a small methanol or chemical tanker while the supply chain, including dedicated barges, develops [59]. An added complexity for methanol bunkering compared to HFO is the need to maintain inert gas coverage both in the barge and on the ship. This is accomplished by creating a closed-loop system where displaced nitrogen-methanol vapor from the ship's tanks is returned to the barge [67]. Methanol bunkering is occurring routinely in Singapore and ports in China. Methanol bunkering demonstrations have taken place in many other ports, including in the United States (Table 5). The first simultaneous methanol bunkering and cargo operations were performed in Singapore in 2024 [68]. Because of the limited availability of green methanol, methanol bunkering has remained limited. For example, in 2025 10,000 mt of green methanol was bunkered in Shanghai, 3,000 mt in Singapore [69], and 12,000 mt in Rotterdam [70]. For comparison, total annual tonnage for all fuels bunkered in Singapore was 56.2 million mt in 2025 [34].

Methanol-capable engines are available for new-build ships from the major engine original equipment manufacturers (e.g., Everllence, Wartsila, WinGD, Caterpillar), including both large two-stroke main engines and smaller auxiliary engines for power generation that may be four-stroke. Ships in service can also be retrofitted to be dual-fuel methanol. Retrofitting is primarily applicable to ships that are between 5 and 10 years old with electronic engine control. Retrofits for dual-fuel methanol operation are a major undertaking that can involve replacing machine parts, hull expansion, adding new fuel tanks, and replacing the fuel preparation room and fuel supply system, along with controls, alarms, and monitoring [71]. For the Maersk Halifax this involved cutting the ship in half to extend the hull by 15 meters [72].

Currently, there are a total of 112 to 120 methanol-capable vessels in operation, including 38 new deliveries in 2026 [32]. Assuming that on average these vessels are large container ships that burn 100 mt per day of fuel oil and using the specific energy values for methanol and MGO in Table 3, these vessels would consume 215 mt per day each. For 112 vessels operating 330 days per year, total methanol demand would be almost 8 million mt per year. Table 5 lists key events in the development of methanol as a fuel for marine shipping, and the most important events are shown graphically in Figure 7.

Table 4. Requirements of IMPCA and ISO 6583:2024 Methanol Specifications

	Units	Method	IMPCA	ISO MMA	ISO MMB	ISO MMC
Appearance		IMPCA 003	Homogeneous, clear, and free of suspended matter			
Purity, dry basis	wt %	IMPCA 001	99.85 min.	99.85 min.	99.85 min.	99.70 min.
Impurities, dry basis	wt %	IMPCA 001	N/A	0.15 max.	0.15 max.	0.30 max.
Acetone	mg/kg	IMPCA 001	30 max.	30 max.	30 max.	30 max.
Ethanol	mg/kg	IMPCA 001	50 max.	50 max.	50 max.	150 max.
Color	Pt-Co	D1209 or D5386	5 max.	N/A	N/A	N/A
Water	wt %	E1064	0.1 max.	0.1 max.	0.1 max.	0.5 max.
Distillation range	°C	D1078	1.0 max.	1.0 max.	1.0 max.	Report
Specific gravity 20°C/20°C		D4052	0.7910– 0.7930	N/A	N/A	N/A
Density at 15°C	kg/m ³	ISO12185/D4052	N/A	795.0– 797.0	795.0– 797.0	795.0– 798.0
Potassium permanganate time at 15°C	minutes	D1363	60 min.	N/A	N/A	N/A
Chloride as Cl ⁻	mg/kg	IMPCA 002	0.5 max.	0.5 max.	0.5 max.	0.5 max.
Sulfur	mg/kg	D5453	0.5 max.	0.5 max.	0.5 max.	10 max.
Water miscibility		D1722	Pass	N/A	N/A	N/A
Carbonizables	Pt-Co	E346	30 max.	N/A	N/A	N/A
Acidity as acetic acid	mg/kg	D1613	30 max.	30 max.	30 max.	30 max.
Iron in solution	mg/kg	E394	0.10 max.	N/A	N/A	N/A
Non-volatile matter	mg/1,000 mL	D1353	8 max.	N/A	N/A	N/A
Lubricity	µm	IP PM FK	N/A	a	--	--
Particle count		IP PM FI	N/A	b	--	--

^a Lubricity shall be agreed upon between buyer and seller.

^b Particle count shall be agreed upon between buyer and seller.

Table 5. Important Events in Methanol Dual-Fuel Shipping

Year	Event
2015	The ferry Stena Germanica was retrofitted to become the world's first dual-fuel methanol vessel (Wartsila four-stroke engine) [73]
2016	Seven new-build chemical tankers were put into service, primarily carrying methanol as cargo [74]
2018	IMO invites ISO to develop a standard for methanol/ethanol as marine fuels [75]
2020	IMO publishes interim guidance on safe handling of methanol and ethanol on board ships [9]
2021	First barge-to-ship methanol bunkering of a methanol tanker in Rotterdam [68]
2023	Laura Maersk, the first methanol-capable container ship (2,100 TEU) maiden voyage from Ulsan, South Korea, to Copenhagen, Denmark [76]
2023	The tankers Stena Pro Marine and Stena Prosperous were refueled with methanol via barge while simultaneously discharging petroleum products for the first-ever methanol bunkering in the Port of Houston and in the United States [77]
2024	Maersk and Everllence complete conversion of Maersk Halifax, a 15,226-TEU container ship, into a dual-fuel methanol vessel [78, 72]
2024	The Stena Provident completed the first-ever methanol bunkering in the Port of Savannah [79]
2024	First-ever simultaneous methanol bunkering with container unloading operations occurred in Singapore [80]
2024	ISO publishes ISO 6583:2024 "Methanol as a fuel for marine applications – General requirements and specifications"
2024	Ane Maersk, the first new-build large (16,000-TEU) methanol-capable container vessel is launched [81]

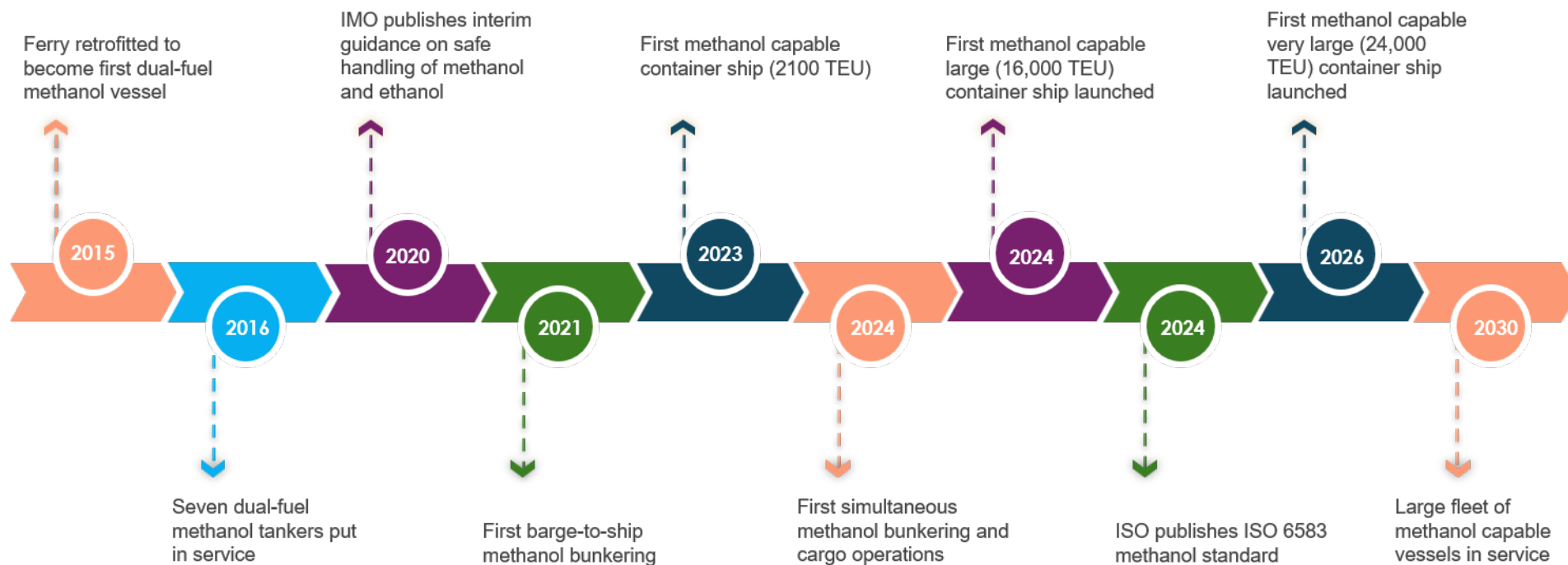


Figure 7. Important events in the development of methanol as a fuel for marine shipping

Comparison of Ethanol and Methanol

The use of both methanol and ethanol is covered in the IMO interim guidance [9]. However, methanol is more mature because of the existence of an ISO standard for fuel quality, port-level standards such as the TR 129 standard for methanol bunking in Singapore [82], and implementation experience with methanol having been used in many ships. Because both methanol and ethanol are alcohols and have similar properties, ethanol may develop very rapidly because of the experience with methanol and the potential for shared infrastructure and a two-alcohol strategy.

Physical Properties and Flammability

Both methanol and ethanol are alcohols and have very similar, but not identical, chemical properties. These are highlighted in Table 6. While similar, the change from one carbon atom in methanol (CH_3OH) to two carbon atoms in ethanol ($\text{C}_2\text{H}_5\text{OH}$) has a relatively small effect on boiling point, density, and flash point but a large effect on LHV. The LHV for ethanol is 35% higher. While methanol's LHV is 54% lower than MGO, ethanol's LHV is only 37% lower. When examined in terms of energy density (on a volume basis), onboard fuel storage must be 2.4 times larger for methanol but only 1.8 times larger for ethanol to have the same vessel range as operation on MGO (38-GJ/m^3 and 850-kg/m^3 density, respectively). Figure 7 shows relative volume required for various alternative fuels compared to MGO [60]. Notably, ethanol requires less fuel storage volume than both methanol and LNG.

Because of their similar flash point, ethanol must be handled using similar procedures for methanol in terms of nitrogen blanketing, fire detection, and ventilation. Fire detection is important because both alcohols burn with a nearly invisible flame that is difficult to detect by human eye. Autoignition temperatures are in the same range as for MGO (250°C – 500°C), providing similar safety from the standpoint of ignition from contact with hot metal surfaces. Methanol's wider flammability range may pose a greater risk of fire or explosion should the inert gas system fail.

Table 6. Comparison of Properties of Methanol and Ethanol

Property	Methanol	Ethanol
Boiling point, $^\circ\text{C}$ ^a	64.7	78.4
Freeze point, $^\circ\text{C}$ ^a	−97	−114
Density at 15°C , kg/m^3 ^b	796.1	793.5
Kinematic viscosity at 20°C , mm^2/s ^g	0.75	1.36
LHV, MJ/kg	19.9 ^c	26.9 ^d
Energy density, MJ/L	15.9	21.4
Heat of vaporization at 25°C , kJ/kg ^a	1,174	918
Flash point, $^\circ\text{C}$ by closed cup method	12 ^c	14 ^e
Autoignition temperature, $^\circ\text{C}$ ^f	464	363
Flammability limits, vol % ^f	6–36	3.3–19

^a NIST webbook [28]; ^b Measurement Canada [29]; ^c Methanol Institute [83]; ^d Christensen et al. [30]; ^e Sigma-Aldrich, Safety Data Sheet for Ethyl alcohol, pure. Product Number: E7023; ^f Ellis and Tanneberger [60]; ^g Engineering Toolbox.

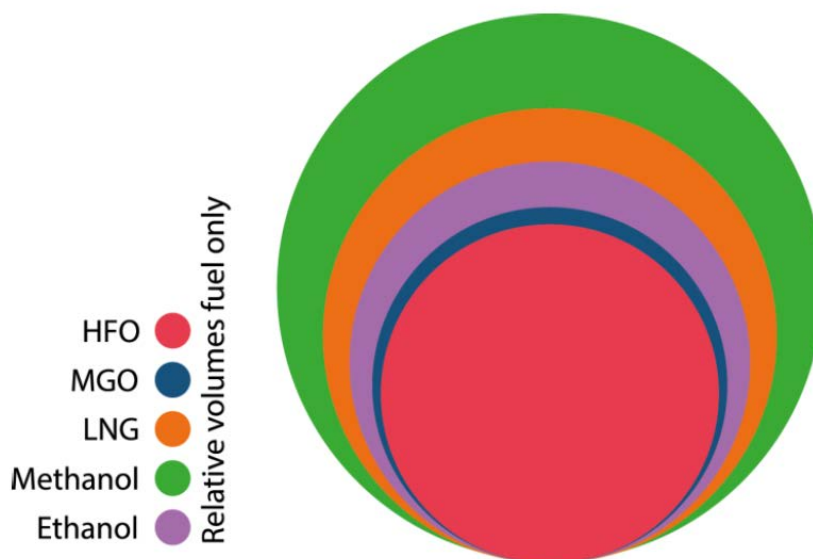


Figure 8. Relative fuel volumes based on energy density [60]

Specifications

ISO published ISO 6583:2024, “Methanol as a fuel for marine applications – General requirements and specifications,” which outlines purity and properties for methanol to be used in the marine market. An ISO specification for ethanol to be used in marine shipping is currently in development, as ISO has created preliminary work item 6583-2, “Alcohols fuel for marine applications – Part 2: Ethanol.” It will likely be based on specifications for ethanol promulgated by ASTM International; the Brazilian National Agency of Petroleum, Natural Gas and Biofuels (ANP); and the European Committee for Standardization (CEN), which are compared to the ISO 6583 methanol specification for grade MMC in Table 7. The MMC grade has the widest range of impurities of the various methanol grades. Because the methanol specification is based on the methanol chemical specification (IMPCA), the allowable levels of impurities are significantly lower than for the ethanol specifications intended for use as a blendstock to make gasoline. The limits on methanol in the various ethanol specifications are because automotive fuel system materials may not be compatible with higher levels, because methanol has a large effect on increasing vapor pressure of gasoline at low blending levels, and methanol can have limited solubility in hydrocarbons. Maximum gasoline vapor pressure is typically regulated to reduce evaporative emissions. These considerations may not be applicable to marine shipping, where engines and fuel supply systems are using nearly pure ethanol or methanol. The methanol ISO specification limit on ethanol concentration of 150 ppm does not appear to have a technical basis, as physical and combustion properties are unlikely to be affected by ethanol concentrations of several volume percent or higher. While ethanol has a higher allowable acidity, experience has shown that ethanol does not increase corrosion rates in common grades of steel. While inorganic chloride at the point of ethanol production is near zero, specifications allow up to 6.7 mg/kg because of contamination in the supply chain. Experience has shown that this low chloride level does not present a corrosion issue. As described in the next section, ethanol producers and distributors routinely add corrosion inhibitor additives to ethanol to protect infrastructure and end user fuel systems.

Table 7. Comparison of Global Standards for Ethanol and ISO6583 MMC-Grade Methanol

Property	Ethanol				Methanol
	ASTM D4806-25	ASTM D8651-25 ^a	ANP No 19/2015 ^b	EN 15376	ISO 6583 (MMC Grade)
Ethanol, vol % min.	92.1	95	98.0		--
Ethanol and higher saturated alcohols, wt % min.				98.7	
Higher saturated (C ₃ –C ₅) mono alcohols, wt % max.				2.0	
Ethanol dry basis, mg/kg max.	--	--	--		150
Methanol, vol % max.	0.5	0.5	0.5	0.300	
Methanol dry basis, wt %	--	--	--		99.70
Impurities dry basis, wt %	--	--	--		0.30
Solvent washed gum, mg/100 mL max.	5	5	--		--
Water, wt % max.	1.26	1.26	0.7		0.500
Inorganic chloride, mg/kg, max.	6.7	6.7	1	1.5	0.5
Copper, mg/mg max.	0.1	--	--	0.1	--
Copper mg/L max.	--	--	0.07		--
Phosphorous, mg/L max.				0.15	
Acidity (as acetic acid), mg/kg	70	70	30	70	30
pH _e	6.5–9.0	6.5–9.0	6.0–8.0	--	--
Sulfur, mg/kg	30	10	Report	10	10.0
Existent sulfate, mg/kg	4	4	4	3.0	--
Denaturant/hydrocarbons, vol %	1.96–2.5	--	3 max.	-- ^c	--
Evaporative residue, mg/100 mL max.	--	--	5	10	--
Alcoholic strength, wt % min.	--	--	99.3		--
Density at 20°C, kg/m ³ max.	--	--	791.5		--
Density at 15°C, kg/m ³	--	--	--		795.0–798.0
Iron, mg/kg max.	--	--	5		--
Sodium, mg/kg max.	--	--	2		--
Electrical conductivity, µS/m max.	--	--	300	2.5	--
Acetone dry basis, mg/kg	--	--	--		30
Distillation range at 101.3 kPa, °C max.	--	--	--		Report

^a Undenatured fuel ethanol.

^b ANP anhydrous grade.

^c As required by national regulations.[†]

ASTM D4806, ANP No. 19, and EN15376 require a denaturant to make ethanol unsuitable for human consumption. This is typically natural gasoline (a byproduct of natural gas production). The need for and impact of denaturants in ethanol for marine shipping is still under discussion. If natural gasoline is undesirable, a specially denatured alcohol with other denaturants can be used. For example, SDA-3A is denatured using 5 vol % methanol (although this would not meet the requirements of ASTM D4806). Alternatively, undenatured fuel ethanol as described in ASTM D8651 can be used.

Because of the similarities of methanol and ethanol, it is possible to imagine a marine fuel market where both are used almost interchangeably as alcohol fuel. This would have the benefit of allowing alcohol-specific bunker barges to switch from one fuel to the other without cleaning and allow ships to load one alcohol on top of a tank partially filled with the other. This is made possible because ship crews closely monitor the amount of fuel in the ship's tanks using soundings and other measurements on a weekly or even daily basis. Careful measurement of the amount of fuel in a tank prior to bunkering new fuel is a critical part of any fuel bunkering operation and allows the captain to calculate the energy content of the mixture of methanol/ethanol in the tank and hence the vessel sailing range.

Materials Compatibility

Generally, methanol is more challenging from a materials compatibility perspective than ethanol. Methanol is more polar and has a higher hydrogen-bonding propensity, which—combined with its smaller molecular size compared to ethanol—leads to a higher degree of interaction with elastomers and plastics. This interaction leads to higher swelling and degradation of the elastomer/plastics physical properties. These properties of alcohols can be quantified in terms of solubility parameters and molar volume [84], as shown in Table 8.

Table 8. Parameters Relevant to Elastomer and Plastics Compatibility of Methanol and Ethanol

	Solubility Parameters			Molar Volume, cm ³ /mole
	Dispersion	Polarity	Hydrogen Bonding	
Methanol	14.7	12.3	22.3	40.6
Ethanol	15.8	8.8	19.4	58.6

From the standpoint of metal corrosion, it is notable that methanol is more acidic than water, while ethanol is less acidic [85]. Additionally, the breakdown product from methanol (formic acid) is a much stronger acid than the breakdown product from ethanol (acetic acid). In the presence of low levels of water, methanol will be more corrosive than ethanol. This is consistent with the recommendation that stainless steel be used for storing methanol (or mild steel tanks having an interior coating) [59], while mild steel may be acceptable for storing ethanol [60]—especially given the common use of corrosion inhibitor additives. Both alcohols are likely corrosive to aluminum alloys and lead and can also promote galvanic corrosion when different metals are in electrical contact.

While not required by specification, it is common to add corrosion inhibitor additives to fuel ethanol at the point of production to protect against corrosion throughout the supply chain, including end user equipment [86]. Many ethanol corrosion inhibitors also include a pH_e

buffering agent to neutralize acids that may form under some conditions [87]. An evaluation protocol for determining the appropriate concentration of the additive has been published [88].

Systems developed for storing and handling methanol should easily be compatible with ethanol.

Methanol and Ethanol Spillage Into the Environment

Kass et al. [43] examined the potential environmental impacts of significant spills or releases of alternative marine fuels, including ethanol and methanol. While these fuels are very similar, there are important differences in their impact when spilled into the ocean. These are highlighted in Figure 9.

Ethanol boils at 78°C and is highly volatile, so it will eventually vaporize if it is left to air. It is completely soluble in water, and if dissolved, its volatility is significantly reduced. When discharged into surface waters, a portion of the ethanol can briefly form a light nonaqueous liquid film on the water's surface, as shown in Figure 9. During and immediately after the spill, ethanol vapors will form over this surface layer, and being denser than air, will displace oxygen near the release point. Ultimately, these vapors will disperse, creating a mixture within the flammable range that can be ignited. But with ethanol's high solubility, this surface layer is quickly removed, primarily by dissolution in the water and secondarily by evaporation. Upon dissolving, ethanol spreads rapidly within the water and then decomposes through microbial activity. The biodegradation half-life of ethanol in water is 6.5 to 26 h [89]. Although ethanol is harmful to marine organisms, its fast dispersion avoids any detrimental effects on those animals or organisms that are nearest to the location of discharge. In addition, ethanol has a low bioconcentration factor—i.e., it does not get accumulated in the food chain.

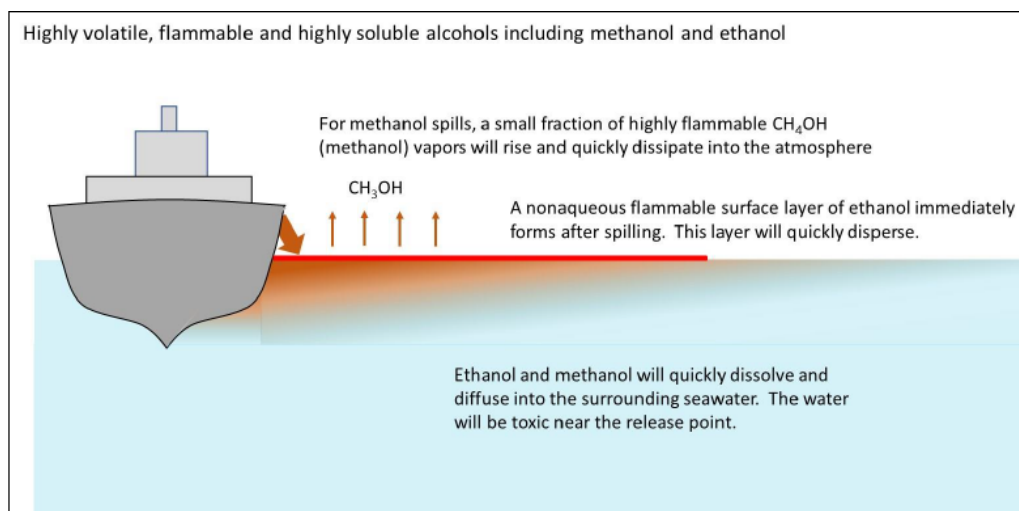


Figure 9. Marine ethanol spill scenario [61]

Because of their similar properties, a methanol spill will have similar behavior. However, methanol has a higher vapor pressure and will evaporate more quickly—methanol vapors will rise and disperse more quickly than is the case for ethanol, such that methanol accumulation on the water surface is unlikely [61]. While there remains a risk of fire during a spill event, most of the methanol will quickly dissolve in water, where it will biodegrade with a half-life of 1 to 7 days—significantly more slowly than ethanol [89].

Thus, while there is a significant risk of fire for spillage of both alcohols, this risk is more quickly abated by evaporation and dispersion into air, and dissolution into water, for methanol. However, once dissolved in water, ethanol will biodegrade more quickly than methanol.

Due to the high miscibility of methanol and ethanol in water, current spill detection technologies may not be able to detect spills. Infrared technologies for oil spill detection that leverage thermal and polarization differences of oil and water cannot be adopted for methanol/ethanol due to similar properties with water. Radar technologies that can detect an oil spill may not be able to detect methanol/ethanol spills as surface wave heights differ. Ultraviolet technologies could be applicable with suitable adaptations [61].

Implementation of Ethanol in the Marine Industry

Regulatory

Ethanol is an approved fuel based on the IMO interim guidelines that include safety requirements, fuel system design, ventilation, leak detection, and firefighting [9]. Maritime classification societies set and enforce technical rules for ship design, construction, and operation that are more detailed than high-level IMO regulations, focusing on the structural and mechanical integrity of vessels throughout their life. Multiple classification societies have published detailed technical requirements for the use of methanol and ethanol including DNV, American Bureau of Shipping, Lloyd's Register, Bureau Veritas, Class NK, and China Classification Society.

For ethanol to be used broadly in shipping, an ISO standard describing its properties needs to be developed. This standard is currently in development by ISO/TC 28/SC 4/WG 18. This group is targeting release of a final standard in 2027.

A driver for alternative fuel use in the maritime industry is the IMO NZF, and the adoption of this framework as legally binding on IMO member states will also be a major driver for use of ethanol in marine shipping. An IMO-recognized pathway and default GFI for U.S. corn-based ethanol is required for a fuel to be recognized under the IMO NZF. A 2021 review found that the carbon intensity of U.S. corn ethanol was 51.4 gCO_{2eq}/MJ—46% lower than for petroleum fuels [26]. U.S. ethanol producers are investing in technology to reduce energy consumption and improve ethanol yields, further reducing this number. Several producers are adopting sequestration of CO₂, which qualifies for a U.S. tax credit and may reduce carbon intensity by as much as 30 gCO_{2eq}/MJ [27].

Engine Status and Trail Voyages

Engine Performance

Both methanol and ethanol are members of the alcohol family, and most of their physical properties are similar. Because methanol is more challenging from a materials compatibility perspective, ethanol is compatible with methanol fuel storage, handling, and injection systems. It is increasingly acknowledged that methanol-capable vessels can operate on ethanol with no or minor modifications, although fully optimized engines would show slightly better performance [90, 91, 92, 93, 94].

In 2025, Everllence confirmed that its large-bore two-stroke ME-LGIM engine designed for methanol dual-fuel could run successfully on ethanol at all load points. The ME-LGIM engine entered service in 2016 in methanol tankers and is one of the more common methanol dual-fuel engines, with 50 engines in operation and 225 on order [95]. A four-cylinder test engine (4S90-LGIM) designed for methanol dual-fuel was operated on both methanol and hydrous ethanol with no major changes to the engine. Performance was acceptable on ethanol, although there was potential to optimize injection and improve thermal efficiency. A second full-scale methanol dual-fuel engine (7G95-LGIM) was also operated on anhydrous denatured ethanol with no changes to the engine with only minor changes to performance relative to methanol. Everllence

has also demonstrated its four-stroke L21/31 in ethanol dual-fuel operation [96]. This engine is in common use for power generation on large ships.

WinGD has tested methanol and ethanol extensively for marine engine applications [97]. The ethanol tests were conducted on an engine designed to operate on methanol. WinGD also conducted spray combustion chamber experiments, where it was shown that the spray propagation of methanol and ethanol is very similar to that of diesel fuel. Results indicated that combustion properties, performance, and emissions are closely comparable and that the same design and safety principles can be applied to both fuels. Because ethanol has a higher LHV than methanol, the engine needs to compensate for the difference in injection quantity between ethanol and methanol to optimize combustion. The injection system originally designed for methanol operation is sufficient to cover ethanol operation without modification. However, nozzle tip geometry can be optimized depending on whether the engine will be operating on methanol or ethanol. WinGD now offers dual-fuel engines that can operate on ethanol, methanol, or a mixture of the two [97]. They have recently accepted orders for two six-cylinder 6X82DF-M/E engines designed to operate primarily on ethanol [98].

Similar studies by Wärtsilä confirm that ethanol and methanol have similar characteristics, meaning the same fuel system and safety precautions as those developed for ethanol can be utilized in current methanol engine platforms with very few modifications [94]. Safety practices and training for operators developed for methanol will also work for ethanol. Studies conducted on a Wärtsilä W6L32M multicylinder engine originally meant for methanol used anhydrous ethanol meeting EN 15376, with slight water content and including 3% isobutanol as a denaturant. Ethanol gave a slightly higher brake-specific energy consumption and lower heat release rates compared to methanol for different loads without hardware modifications and without changes in the control system settings.

Caterpillar has also acknowledged that it is exploring the use of ethanol in its dual-fuel methanol marine four-stroke engines [99].

Alcohol dual-fuel engines easily meet Tier I and Tier II emission requirements, including NO_x, when running in dual-fuel mode. Meeting Tier III NO_x emissions requires additional controls such as urea selective catalytic reduction.

Trial Voyages

Public reports of sea trials using ethanol dual-fuel systems are limited to the trials on *Laura Maersk*—the world’s first methanol-capable container ship powered by an Everllence 6G50ME-C9.9-LGIM engine. From October to December of 2025, trial voyages were conducted in the Baltic Sea using a blend of 10% ethanol in methanol, which confirmed that this blend could be used without compromising engine performance. A second trial using a 50% ethanol blend was initiated in December 2025 and was also successful [100]. A third trial using 100% anhydrous denatured ethanol was conducted in early 2026 and was also successful, with no challenges to the use of ethanol noted [101].

Bunkering and Availability in Ports

Recently, there have been major milestones in commercial ethanol bunkering. In May 2026 *Laura Maersk* completed barge-to-ship bunkering of 2,000 mt (670,000 gal) of ethanol in

Rotterdam [102]. Also during May in Rotterdam, the X-Press Feeders container ship Eco Levant separately bunkered 90% biomethanol and 10% ethanol in a barge-to-ship transfer, with the two alcohols mixed in the onboard tank [103]. In July, the 16,000-TEU container ship Antonia Maersk bunkered 2,800 mt (938,000 gal) of ethanol in a barge-to-ship transfer in Barcelona [104]. All of these ships have then operated on the bunkered fuel in commercial operation. Efforts to bunker ethanol in the United States are in the planning stages [105].

Ethanol is available in ports where it is exported or imported. The specific ports used for export and import of ethanol in the United States may be significant for use of ethanol as a marine shipping fuel, as these ports have ethanol storage and handling facilities that presumably could supply ethanol to ships. Nearly half of U.S. ethanol exports are out of Houston, with another 12% out of New Orleans, and significant exports through New York and Seattle as well [24]. Ethanol imports, although very small, were almost entirely to the Port of Savannah in 2024.

A challenge in understanding how to implement ethanol as a maritime fuel in the United States is a lack of data on bunkering tonnage in U.S. ports, and what types of vessels are bunkering. Sources suggest that the total U.S. bunkering market in 2025 was approximately 18 million mt [35]. The Greater Houston area is thought to have the largest market at 4–5 million mt annually. Port statistics from Los Angeles, one of the few U.S. ports offering such data, suggest a total bunker tonnage of 1 million mt in 2025 [106].

We can estimate a cap on the near-term market by looking at potential ethanol consumption by the current operating fleet of 112 methanol dual-fuel ships. Assuming that these are on average large container ships that consume 100 mt of fuel oil per day, this translates into 160 mt per day of ethanol. Annually, ethanol consumption would be nearly 6 million mt or nearly 2 billion gallons (for 330 days of operation) under this scenario.

Ethanol Price Compared to Alternatives

A price comparison is shown in Table 9 for both February 2026 (pre-Iran war) and June 2026. Prices for methanol and ethanol are shown per metric ton, and on a VLSFO-equivalent (VLSFO_{eq}) basis. VLSFO_{eq} prices are multiplied by the ratio of VLSFO specific energy (assumed to be 43 MJ/kg) to alcohol specific energy (a ratio of 2.161 for methanol and 1.599 for ethanol). This reflects the additional alcohol that would have to be purchased to have the same energy and vessel range as VLSFO. These prices are just a snapshot of two specific dates and are only intended to provide a rough estimate of relative pricing. The following discussion of prices is on an energy equivalent basis.

In February, gray methanol was 65% more expensive than VLSFO, while ethanol was roughly twice as expensive. However, in June ethanol prices had only gone up 10%, likely reflecting increased gasoline demand in the summer months in the United States, such that ethanol was only 43% more expensive than VLSFO. VLSFO and gray methanol prices had increased by much more significant amounts. Citable prices for green methanol are difficult to find but based on a single quote for biomethanol in Rotterdam, they are on the order of twice the price of ethanol.

Table 9. Prices of VLSFO Compared to Gray Methanol, Green Methanol, and Ethanol

\$/mt (\$/gal)	Feb. 2026	June 2026
VLSFO ^a	455 (1.64)	744 (2.68)
Gray methanol ^a	365 (1.10)	554 (1.67)
Gray methanol VLSFO _{eq}	751 (2.26)	1,140 (3.43)
Green methanol ^b	--	988 (2.98)
Green methanol VLSFO _{eq}	--	2,033 (6.13)
Ethanol ^c	591 (1.78)	666 (2.00)
Ethanol VLSFO _{eq}	944 (2.84)	1,064 (3.20)

^a Prices for Houston from shipandbunker.com.

^b Green methanol (biomethanol) price for Rotterdam, mid-May 2026 [107].

^c Ethanol prices from U.S. Grains & BioProducts Council [108].

Summary of Ethanol Implementation

Table 10 and Figure 10 show major events that have occurred to date in the implementation of ethanol in marine shipping. Critical events have been unfolding at a very rapid pace since late 2025.

Table 10. Major Events in the Implementation of Ethanol in Marine Shipping

Year	Event
2018	WinGD conducts full-scale engine tests of ethanol dual-fuel engine [97]
2018	IMO invites ISO to develop a standard for methanol/ethanol as marine fuels [75]
2020	IMO publishes interim guidance on safe handling of methanol and ethanol on board ships [9]
2025	The ship Laura Maersk completes successful trial of 10% ethanol in methanol blends and embarks on a 50%-blend-level trial with a 100% ethanol trial to follow [100]
2025	Everllence demonstrates that Everllence's ME-LGIM methanol dual-fuel engine can operate on ethanol at all load points [95]
2025	WinGD announces it will introduce an ethanol dual-fuel two-stroke engine in 2026 [97]
2025	Wartsila publishes paper at CIMAC showing that ethanol can be used in a methanol-optimized engine, but that higher thermal efficiency can be realized with further development [94]
2025	ISO initiates preliminary work item 6583-2, "Alcohols fuel for marine applications – Part 2: Ethanol"
2026	HD Hyundai Heavy Industries confirmed that its four-stroke H32DF-LM dual-fuel methanol engine exhibits stable operation on ethanol at all load points. The engine is used for power generation on commercial ships [109]
2026	Successful trial of 100% denatured fuel ethanol in Laura Maersk [101]; commercial ship-to-ship bunkering of Laura Maersk with 2,000 mt of ethanol [102]
2026	Commercial bunkering of 16,000-TEU container ship Antonia Maersk with 2,800 mt of ethanol in a barge-to-ship transfer in Barcelona [104]

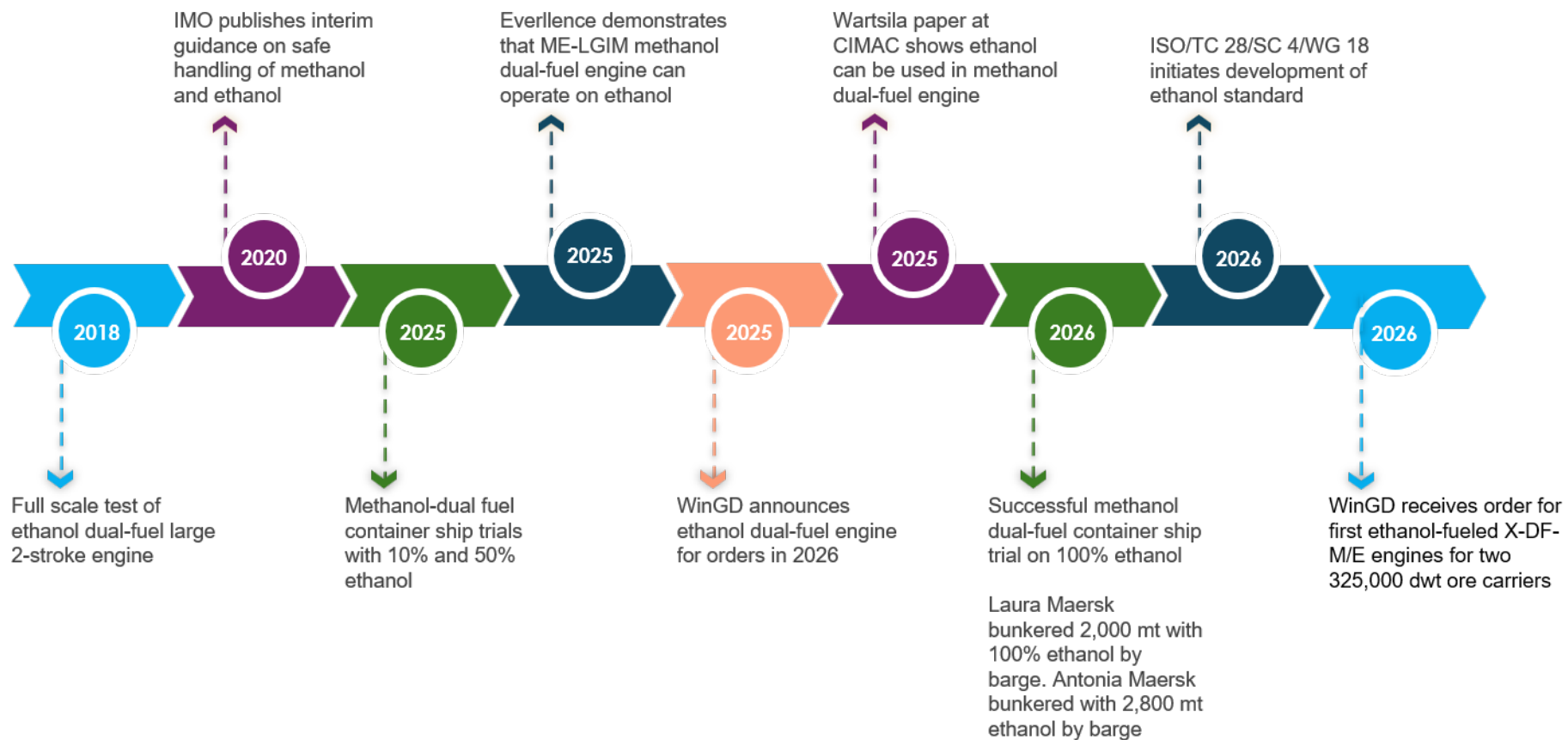


Figure 10. Important events in the development of ethanol as a fuel for marine shipping

Summary and Remaining Barriers

This report examines whether ethanol can become a viable marine fuel and compares it extensively with methanol, which is already gaining adoption in shipping. The report concludes that ethanol is technically feasible for marine use and could leverage much of the infrastructure, engine technology, and operational experience already developed for methanol. However, large-scale adoption will depend on regulatory progress, fuel standards, bunkering infrastructure, and recognized life cycle carbon accounting.

Marine shipping currently employs HFO and VLSFO, consuming roughly 211–259 million mt of fuel annually for IMO-regulated international shipping, with broader estimates exceeding 300 million mt globally. Shipping emissions are regulated by IMO, including SO_x, NO_x, and PM. Alternative fuels such as biodiesel, methanol, and ethanol can help to meet these emissions requirements and are being evaluated as pathways toward IMO decarbonization goals.

A central finding is that ethanol shares many important properties with methanol. Existing methanol-capable dual-fuel marine engines can operate on ethanol with little or no modification. Major engine developers, including Everllence, WinGD, Wärtsilä, and HD Hyundai have successfully tested ethanol in methanol-designed engines. Trials demonstrated acceptable combustion behavior, comparable emissions characteristics, and stable operation across engine loads. WinGD has announced production of ethanol-capable dual-fuel engines. Commercial trials have occurred aboard Maersk vessels using Everllence engines.

The report highlights several advantages of ethanol relative to methanol. Ethanol has approximately 35% higher energy content than methanol, lower human toxicity, and potentially lower life cycle greenhouse gas emissions when produced from bio-based feedstocks. A cited study estimated U.S. corn ethanol at approximately 51.4 gCO_{2eq}/MJ, about 46% lower than petroleum fuels, with additional reductions possible through carbon capture and sequestration at ethanol plants.

At the same time, ethanol presents operational and safety considerations similar to those for methanol. Its flash point of 14°C requires inert gas blanketing and specialized handling during storage and bunkering. Like methanol, ethanol is fully miscible with water and highly flammable. Ethanol spills in marine environments will disperse and biodegrade relatively quickly, with biodegradation half-lives between 6.5 and 26 hours in water. Although ethanol is harmful to marine organisms at high concentrations, rapid dissolution and low bioaccumulation reduce long-term environmental persistence compared to conventional oil spills. Methanol behaves similarly but biodegrades more slowly once dissolved.

The report also reviews fuel standards and regulatory development. IMO interim safety guidance already permits the use of methanol and ethanol aboard appropriately designed ships. ISO has finalized a marine methanol specification (ISO 6583:2024), while a corresponding ethanol marine fuel standard, ISO 6583-2, is under development. Existing ethanol standards were largely created for automotive gasoline blending rather than marine fuel applications, so additional specification work is needed.

Economically, the report identifies marine shipping as a potentially large future market for ethanol producers. Theoretical maximum demand for ethanol in IMO-regulated shipping could reach approximately 355 million mt (118 billion gallons) annually, although the report acknowledges that full displacement of conventional fuels is unlikely. Even partial adoption could create demand measured in billions of gallons per year. The report estimates that the currently operating methanol dual-fuel fleet alone could consume roughly 2 billion gallons of ethanol annually under high-substitution scenarios.

Ethanol is technically viable as a marine fuel and benefits from compatibility with methanol infrastructure and engines. Remaining barriers include development of ethanol bunkering infrastructure at ports, completion of international fuel specifications, supply chain investment, and establishment of IMO-recognized life cycle greenhouse gas intensity values for ethanol.

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