



Mærsk Mc-Kinney Møller Center
for Zero Carbon Shipping

Ethanol as a marine fuel: exploring its usability



Energy systems and fuel pathways, October 2026

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Executive summary

Decarbonizing the shipping industry requires access to low-emissions fuels. Researchers and industry have identified several low-emissions fuels with relevance to shipping – for example, methanol, ammonia, and biodiesel. However, many of these fuels have limited availability, at least in the near term.

To help respond to this challenge, the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) is working with our partners to investigate ethanol's potential as a marine fuel. Ethanol is an alcohol with similar properties to methanol and is currently produced at large volumes. In this report, we focus on ethanol's technical usability in shipping contexts. Important considerations relating to ethanol's sustainability and scalability will be covered separately.

This report begins with a brief overview of the context behind ethanol as a marine fuel. The following main sections each explore a specific use case for ethanol as a marine fuel:

(1) using ethanol in engines designed for methanol operation, and

(2) ethanol-diesel blends as a potential option for existing diesel engines.

We then outline some topics for further consideration, followed by the report's conclusions.

The report's first main section highlights the increasing interest from engine developers and vessel owners in ethanol as a viable drop-in fuel for engines designed for methanol operation. Multiple studies and announcements indicate that fuel systems designed for methanol can be successfully recalibrated to combust ethanol. Onboard emissions, material compatibility, and regulatory considerations for onboard use of methanol and ethanol appear to be broadly similar. The remaining challenges for this ethanol use case relate mainly to optimization, validation, and certification. Taken together, these reported findings paint a clear pathway for ethanol's use in methanol-fueled vessels.

With that said, most of the existing fleet is not built to operate on methanol. The second main section investigates blending ethanol with marine gas oil (MGO) as an option to reduce emissions from these existing vessels. Our laboratory tests showed that ethanol-MGO blends had a low flashpoint and a tendency to separate during longer-term storage. In addition, we identified the risk of blend separation when the fuel blend passes through the onboard fuel preparation system. However, we also found reports of potential solutions to these challenges, such as fuel additives to increase the flashpoint and blending technologies to address separation issues.

While we were unable to independently replicate the reported flashpoint-increasing effects of two fuel additives, our tests were not exhaustive. If increasing the flashpoint of ethanol-MGO blends ultimately proves infeasible, ships operating with ethanol must be equipped with dedicated safety systems. Recent industry announcements of commercial kits for retrofitting conventional engines for operation on ethanol blends, and onboard devices that blend ethanol with conventional fuels on demand, demonstrate the wider industry's ongoing efforts to overcome these technical challenges.

Building on these findings, we further investigated the option of partially retrofitting an existing vessel to ensure compliance with safety requirements for low-flashpoint fuels. We share the results of a techno-economic assessment of retrofitting a Kamsarmax bulk carrier for ethanol-MGO operation, assuming a framework of emissions intensity targets and compliance mechanisms in line with the draft International Maritime Organization Net-Zero Framework (IMO NZF). Our results indicate that this type of retrofit could be a commercially viable option for vessels with high fuel consumption, operations primarily in sulfur emission control areas, or with access to ethanol with low emissions intensity.

Overall, we find that ethanol shows an encouraging level of technical usability in shipping. Besides the already established use for methanol-fueled vessels, the option to retrofit conventional engines to use blends might open an important avenue for ships that are too old to be targeted for full engine retrofit. While using ethanol in conventional engines presents a few challenges, our research indicates that technical solutions to these challenges are available, and that the overall use case can be commercially attractive under certain conditions.



01 The bigger picture behind ethanol as a marine fuel

Rapid progress in the development of methanol as a low-emissions marine fuel has been reflected in early rising orders for methanol dual-fuel ships. However, delays in low-GHG methanol production projects have resulted in limited availability of bio- and e-methanol,¹ raising concerns that fuel availability challenges could work against methanol's broader adoption.^{1,2} Against this backdrop, ethanol is emerging as a potential marine fuel that could support shipping's decarbonization efforts, especially as a complementary fuel in the methanol pathway.³

Molecularly, ethanol (C_2H_5OH , also called ethyl alcohol) is an alcohol that is very similar to methanol (CH_3OH , also called methyl alcohol). Compared to methanol, ethanol has a higher energy density and significantly lower toxicity. Looking at production strictly from renewable sources, ethanol also has larger existing production volumes than methanol. Greenhouse gas (GHG) emissions associated with ethanol vary widely based on feedstock, agricultural practices, land-use impacts, and regional production pathways. As such, sustainability aspects of ethanol require a detailed analysis and will be addressed in further reports from this project. These upcoming reports will focus on sustainability and GHG emissions.

In this report, we focus on the practical application of ethanol as a marine fuel, examining where and how it could be used today and in tomorrow's fleet. Our analysis covers two main pathways:

Using ethanol in engines developed for methanol operation

Early assessments from original equipment manufacturers (OEMs) indicate that adaptations could offer shipowners greater fuel flexibility. Since this application of ethanol has already attracted significant interest from engine developers and shipping companies, this section focuses on synthesizing publicly reported results and announcements.

Blending ethanol with conventional fuels in the existing fleet

Most of the existing fleet is not designed for operation on low-flashpoint alcohols, raising the question of whether ethanol could also be used in these vessels. In this section, we report original insights from laboratory tests on the properties of ethanol-diesel blends and share the results of a retrofit case study addressing the challenges posed by ethanol's low flashpoint.

Following these two main analysis sections, we close this report with some suggested areas for future work and takeaway messages.

1.1 About this project

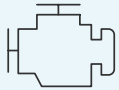
The work shared in this report is part of a larger project on 'Sustainable drop-in biofuels for marine use', led by the MMMCZCS.⁴ The overall project aims to explore options to increase the availability of sustainable and suitable drop-in fuels for shipping. Project work is conducted under competition law-compliant protocols: neutral facilitation, public or anonymized/aggregated inputs only, and no coordination on commercial conduct.

Within the broader project, this report forms part of a work package on ethanol's potential as a marine fuel. The MMMCZCS and our partners NORDEN, TotalEnergies, and ABS participated in the work on ethanol usability presented in this report. Future planned publications will address other aspects of ethanol as a marine fuel.



02 Using ethanol in engines developed for methanol operation

Determining whether ethanol can be used in existing methanol dual-fuel engines involves several considerations:



Combustion

Verifying that the engine can burn ethanol efficiently and with performance comparable to that of methanol.



Emissions

Quantifying engine emissions, including NO_x, particulate matter, and unburned hydrocarbons, and the implications for engine certification.



Safety

Ensuring that ship operations are safe for the crew, the asset, and the environment, and that the vessel is never at risk of losing propulsion.



Material compatibility

Ensuring that components in the methanol fuel supply and engine systems can also tolerate ethanol.

Preliminary laboratory and engine-bench testing have answered many of the initial questions. The next step for OEMs would be targeted development activities to turn these findings into solutions that can be deployed reliably and at scale across the industry.

2.1 Fuel properties, combustion behavior, and operational implications

Due to their similar chemical and physical properties, ethanol and methanol have broadly similar combustion behavior in dual-fuel methanol engines. Ethanol's energy density is higher than that of methanol: around 27 MJ/kg and 20 MJ/kg, respectively, with similar densities. From a practical point of view, this means that ethanol requires a smaller volume of onboard fuel storage to achieve a given vessel range.

Since ethanol releases more energy per injected mass than methanol, engines designed for methanol operation require shorter and/or differently timed injections to achieve the same power output. The resulting influences on mixture formation, combustion phasing, and emissions can generally be managed through calibration of injection pressure, timing, and other control parameters. Without this tuning, engine efficiency and emissions performance would not be optimal, reflecting software calibration needs rather than hardware limitations.

A 2019 conference paper reported that ethanol and methanol behave similarly in research engine testing, with ethanol able to deliver stable combustion when the fuel system is calibrated for this fuel's higher energy content.⁵ The same paper reported that ethanol demonstrated lower smoke formation compared to diesel, as well as favorable low-load fuel consumption.⁵ A more recent paper reported a longer total combustion duration for ethanol compared to methanol, which may, e.g., reduce combustion efficiency and increase emissions of particulate matter in engines originally tuned for methanol operation.⁶ Taken together, these results suggest that ethanol can serve as a viable alternative to methanol in multi-cylinder engines, offering comparable performance with minimal adjustments to existing engine settings.⁶



2.2 Emissions certification, material compatibility, and regulatory considerations



Emissions certifications

Recent engine tests have reported similar NO_x levels for ethanol and methanol, with lower weighted NO_x emissions for ethanol under the ISO 8178 D2 test cycle.⁶ The same study reported that ethanol and methanol produced similar emissions of hydrocarbons, particulate matter, and formaldehyde, while ethanol produced lower unburned fuel and increased carbon monoxide (CO) emissions.⁶

Engines operating on fuel oil, methanol, and ethanol must demonstrate compliance with International Maritime Organization (IMO) Tier II and Tier III requirements for each fuel as per MARPOL Annex VI Regulation 13.⁷ For new engines, this compliance can be demonstrated through test-bed trials. Existing engines would require more complex additional certification work involving back-to-back fuel testing, either through parent-engine testing or onboard trials.



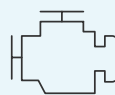
Material compatibility

Most materials used in methanol fuel systems are generally expected to be suitable for ethanol, with no major changes in material selection anticipated.^{8,9}



Safety

From an operational perspective, ethanol and methanol share similar low-flashpoint characteristics. The IMO has issued non-mandatory Interim Guidelines for ships using methyl/ethyl alcohol as fuel (MSC.1/Circ.1621),¹⁰ which currently form the regulatory basis for both fuels. Mandatory IGF Code requirements are still under development, with the IMO aiming to incorporate them into the Code by 2027.¹⁰ As a result, the rules, guidelines, and handling procedures specified in MSC.1/Circ.1621 can largely be applied to ethanol, but only within the scope of the current interim framework.



Ethanol specifications

Another regulatory consideration for ethanol relates to denaturation. In most countries, ethanol must be denatured to make it unfit for human consumption when sold as fuel. For example, in the United States, ethanol fuel for the automotive sector must contain 2-5% gasoline as specified in 27CFR §21.151.¹¹ In Europe, EN 15376 permits denaturants such as isobutanol, isopropanol, and methyl tert-butyl ether.¹² When considering ethanol as a marine fuel, the choice of denaturants should be evaluated alongside material compatibility, corrosion behavior, water tolerance, and lubricity requirements. ISO has established a working group (ISO/TC 28/SC 4/WG 18) to develop a standard for ethanol as a marine fuel.¹³

2.3 Overall outlook

Across combustion tests, material assessments, and early engine trials, ethanol appears technically compatible with methanol-capable engines – provided that control-system settings are adapted accordingly.

With appropriate calibration, ethanol can match or closely approach methanol's performance and emissions profile. The picture therefore looks promising for ethanol's potential as an additional fuel option for methanol-fueled vessels. The remaining steps in this context relate primarily to optimization, validation, and certification rather than fundamental technical barriers.

Industry announcements from engine developers and vessel owners

Wärtsilä

In October 2023, Wärtsilä announced a strategic partnership with Raízen to explore and test ethanol in marine engines, with the long-term goal of enabling ethanol's introduction into the shipping industry.¹⁴ Results from engine tests were presented at the CIMAC Conference in 2025 and collected in a publication.⁶ In March 2025, Wärtsilä announced a world-first trial using ethanol for large-scale electricity generation, in partnership with Brazilian energy company Energetica Suape II S.A.¹⁵

WinGD

WinGD's ethanol research and development program was initiated in 2014. In September 2025, WinGD announced plans to offer the first ethanol-fueled two-stroke marine engines from 2026, with deliveries for both newbuilds and retrofits expected from 2027. The company also shared its intention to support the ethanol value chain by becoming a founding member of the Global Ethanol Association.¹⁶

Everllence

In September 2025, Everllence reported successful operation of its 90-bore 4S90ME-C10.5-LGIM two-stroke engine running on ethanol at all load points.¹⁷ In December of the same year, Everllence announced a demonstration of its 21/31 four-stroke dual-fuel engine's ethanol capability, operating the platform on ethanol at all load points.¹⁸

Hyundai HiMSEN

In December 2025, HD Hyundai Heavy Industries reported successful testing of ethanol operation of its HiMSEN dual-fuel four-stroke engine. The test showed stable performance with only minor modifications to the methanol engine platform. The company will next conduct durability tests to meet class requirements, supporting long-term reliability assessments.¹⁹

Caterpillar

In July 2026, Caterpillar reported the commercialization of conversion kits for their MaK M 32 and M 43 four-stroke diesel engines into methanol and ethanol dual-fuel platforms. The company indicated that, after conversion, the M 32 and M 43 engines will be capable of operating on 95% methanol or ethanol by volume.²⁰

Maersk

In the last quarter of 2025, Maersk conducted an onboard trial of a 10% ethanol/90% e-methanol blend on board Laura Maersk, a dual-fuel methanol container vessel. Based on the outcome of this trial, Maersk announced its plans to test a 50-50 ethanol-methanol blend.²¹ In June 2026, Maersk reported that it had also successfully completed trials using 100% ethanol on Laura Maersk.²² One of these trials also included a larger-scale bunkering operation to validate operational handling under commercial conditions.²²

03 Ethanol-diesel blends as a potential option for existing diesel engines

In this section, we turn to the majority of the global fleet still powered by conventional diesel engines. Most existing vessels lack dual-fuel capability, while cost and operational constraints make full retrofits unlikely. For these ships, biodiesel is currently the only widely available low-carbon drop-in option. The global supply of biodiesel is limited, with demand from aviation and road transport creating strong competition for the same feedstocks.

In this context, ethanol-diesel blends could offer a potential pathway to reducing GHG emissions from existing diesel engines without a full engine retrofit. However, this pathway presents some important technical challenges:

- Flashpoint: Ethanol's low flashpoint may reduce the flashpoint of the overall blend below the marine safety requirements of a minimum of 60°C, as required by SOLAS Regulation II-2/4.1.1.1.²³
- Blend stability: Blended ethanol and diesel may separate during storage or circulation in the fuel system, particularly under varying temperatures.

To better understand these key challenges, the MMCZCS and our strategic partners NORDEN and TotalEnergies have worked together to evaluate the usability of high-purity ethanol (>99%) blended with MGO (DMA grade, ISO 8217 Table 1). In Sections 3.1 and 3.2, we share the results of tests conducted by TotalEnergies on the flashpoint and stability of the resulting ethanol-MGO blends. Section 3.3 examines the option of onboard fuel blending, while Section 3.4 shares the results of our techno-economic analysis of retrofitting a vessel for operation on blends of ethanol and MGO.

We focused on MGO as a more practical blending candidate than very low-sulfur fuel oil (VLSFO). Due to its high viscosity, VLSFO is usually heated to 70-90°C before onboard purification – reducing its suitability for onshore blending with ethanol, which has a boiling point of 78°C at 1 bar. By contrast, MGO's lower viscosity means that it does not require heating. In fact, some operators skip MGO purification, while others run separators in clarifier mode without water at ambient engine-room temperatures.

In addition to the two key challenges discussed here, blending ethanol with diesel presents some secondary challenges, including:

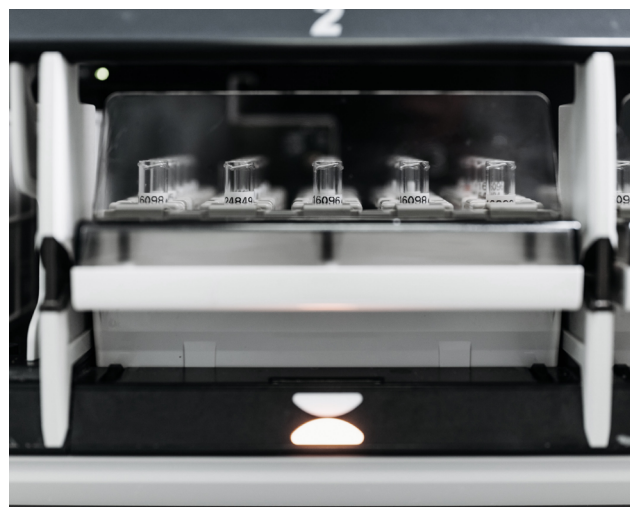
- Viscosity: Ethanol's very low viscosity can fall below the minimum thresholds required for proper lubrication in marine fuel injection equipment, potentially increasing wear or internal leakage.
- Material compatibility: Certain elastomers, seals, and metallic components used in conventional diesel engines may not be fully compatible with ethanol. Existing materials should therefore be assessed for suitability and components upgraded if necessary.
- Engine type: Ethanol-diesel blends are likely feasible only in electronically controlled engines, which can be tuned to accommodate different combustion behaviors. These engines dominate post-2010 newbuilds and are standard on large commercial vessels, which consequently represent the practical candidates for ethanol retrofits. Upgrading older, mechanically controlled engines is rarely economical.

3.1 Flashpoint and short-term solubility assessment

We conducted flashpoint tests following the ASTM D56 standard and using an Anton Paar Tagliabue TAG 500 measuring device. As ethanol's flashpoint is below room temperature, samples containing ethanol were stored at 0–5°C before measurement. Due to the difficulty of precisely measuring these low-flashpoint fuels, the repeatability of the flashpoint measurements was around $\pm 2.7^\circ\text{C}$.

As a general rule, a mixture's flashpoint is governed by its most volatile component. We confirmed that even small additions of ethanol (10 wt%) lowered the flashpoint of ethanol-MGO blends to close to that of pure ethanol (11°C) (Table 1) and well below the SOLAS threshold (60°C).

We therefore tested two compounds that had been previously reported to increase the flashpoint of alcohol-diesel blends or volatile solvents: biodiesel and α -terpineol.^{24,25} However, adding biodiesel did not significantly increase the flashpoints of pure ethanol, MGO, or ethanol-MGO blends in our tests (Table 1). We were also unable to reproduce the reported results for α -terpineol, as the flashpoint of ethanol mixed with 14% α -terpineol was only a few degrees higher than that of pure ethanol in our tests (Table 1). With the resources available in this project, we were unable to further investigate these or other additives. We decided to share our findings so far in this report, while noting that literature from other industries on increasing flashpoint suggests some additional avenues for further investigation.^{26–28}



Altogether, the results from these tests confirm that ethanol's volatility drives the flashpoint of ethanol-MGO blends well below the SOLAS 60°C limit. Retrofitting of the fuel system to accommodate the blend's low flashpoint may enable the use of these blends in existing diesel-powered vessels (see Section 3.4).

To support economic assessments of retrofitting existing vessels to run on ethanol-MGO blends, we next investigated the solubility limit of ethanol in MGO (Table 1). Vials were shaken for 15 minutes and then visually inspected. After resting the vials for 1 hour at room temperature, the densities of the upper and lower phases were measured using a PAC (ISL VIDA 40) density meter following the NF EN ISO 12185 standard. We found that ethanol is miscible in MGO up to 47.5 wt%. At 50 wt% ethanol, the blend could not form a single phase and separated into distinct layers.

Table 1: Results of flashpoint and short-term solubility tests performed by TotalEnergies.

		Flashpoint (°C)	Solubility after blending by visual appearance	Solubility after 1h (difference in density between top and bottom phases)
Individual components	100% MGO	73.5		
	100% ethanol	11		
	100% biodiesel	>130		
Influence of ethanol and ethanol-biodiesel on MGO flashpoint	90% MGO 10% ethanol	13.5	Homogeneous & clear	Homogeneous (0.1 kg/m ³)
	80% MGO 10% ethanol 10% biodiesel	14.5	Homogeneous & clear	Homogeneous (0.2 kg/m ³)
	90% MGO 10% biodiesel	75.5	Homogeneous & clear	
	80% MGO 20% biodiesel	77.5	Homogeneous & clear	
Influence of biodiesel on MGO flashpoint	90% ethanol 10% biodiesel	14	Homogeneous & clear	
	80% ethanol 20% biodiesel	13	Homogeneous & clear	
	70% ethanol 30% biodiesel	13.5	Homogeneous & clear	
	86% ethanol 14% α-terpineol	14		
Influence of α-terpineol on ethanol flashpoint	60% MGO 40% ethanol		Homogeneous & clear	Homogeneous (0 kg/m ³)
	57.5% MGO 42.5% ethanol		Homogeneous & clear	Homogeneous (0 kg/m ³)
	55% MGO 45% ethanol		Homogeneous & clear	Homogeneous (0.1 kg/m ³)
	52.5% MGO 47.5% ethanol		Homogeneous & clear	Homogeneous (0.1 kg/m ³)
	50% MGO 50% ethanol		Not homogeneous	
Assessment of ethanol solubility in MGO				

MGO = marine gas oil

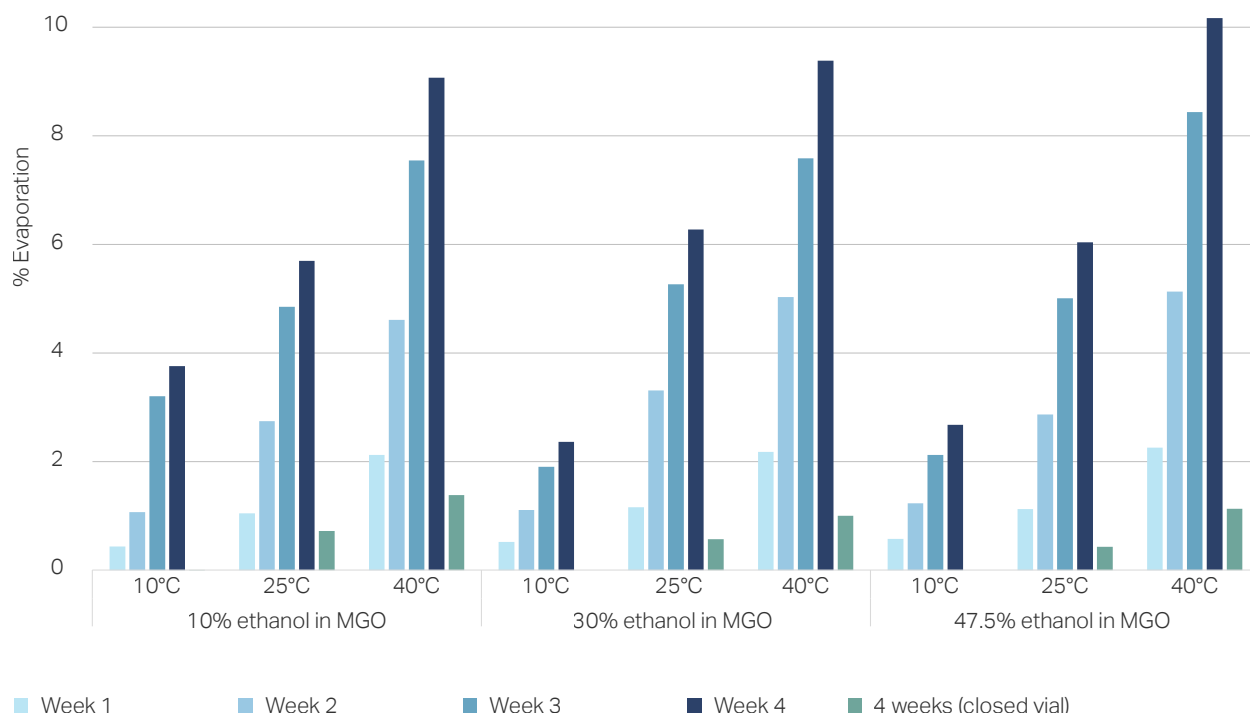
3.2 Long-term solubility assessment

To understand the longer-term solubility, we conducted a four-week stability assessment at 10, 25, and 40°C for ethanol-MGO blends containing 10, 30, and 47.5 wt% ethanol (Figure 1). Samples were stored either closed or partially opened to allow

daily vapor release. In closed storage, we observed no weight change after four weeks for the samples stored at 10°C, while warmer storage temperatures showed around 1% evaporation.

For the partially opened samples, we recorded 2-10% evaporation. Evaporation rates increased with storage temperature but were not noticeably affected by ethanol concentration.

Figure 1: Evaporation rate as a function of temperature (10, 25, 40°C) for ethanol-MGO blends (10%, 30%, and 47.5% ethanol) over time.



MGO = marine gas oil

All three blends showed phase separation after one week of storage at 10°C (Table 2). Storage at 25°C or 40°C yielded better stability, but the longer-term stability of the blends decreased with increasing ethanol concentration. For example, the 10% and 30% ethanol blends remained stable over four weeks when stored at 40°C, while the 47.5% ethanol blend began to separate from Week 3 onward.

Although all blends could be re-homogenized by shaking, the repeated phase separation highlights clear limitations for onshore storage or onboard handling of these blends prior to engine use. Therefore, onboard blending may offer a more robust approach.

Table 2: Visual rating of samples (ethanol blended with marine gas oil) in a storage stability study.

Ethanol concentration	Storage temperature	Start	1 week	2 weeks	3 weeks	4 weeks
10% ethanol	10 °C	Clear & bright	2 phases	2 phases	2 phases	2 phases
	25 °C	Clear & bright	Clear & bright	Clear & bright	Clear & bright	Clear & bright
	40 °C	Clear & bright	Clear & bright	Clear & bright	Clear & bright	Clear & bright
30% ethanol	10 °C	Clear & bright	2 phases	2 phases	2 phases	2 phases
	25 °C	Clear & bright	Clear & bright	2 phases	2 phases	2 phases
	40 °C	Clear & bright	Clear & bright	Clear & bright	Clear & bright	Clear & bright
47.5% ethanol	10 °C	Clear & bright	2 phases	2 phases	2 phases	2 phases
	25 °C	Clear & bright	Clear & bright	2 phases	2 phases	2 phases
	40 °C	Clear & bright	Clear & bright	Clear & bright	2 phases	2 phases

3.3 Onboard blending

Onboard blending of fuels before engine inlet presents a potential solution to blend instability, as fuels can be mixed on demand. This helps avoid separation of fuel blends during storage or in the fuel preparation system.

We found a recent report of an alcohol-diesel emulsion booster module, designed to enable existing marine diesel engines to operate with up to 30% alcohol blended with MGO (Figure 2).²⁹ This product works by creating a stable, controlled alcohol-diesel blend via automated dosing, real-time viscosity and density monitoring, and a closed-loop mixing system designed to prevent phase separation and alcohol evaporation.

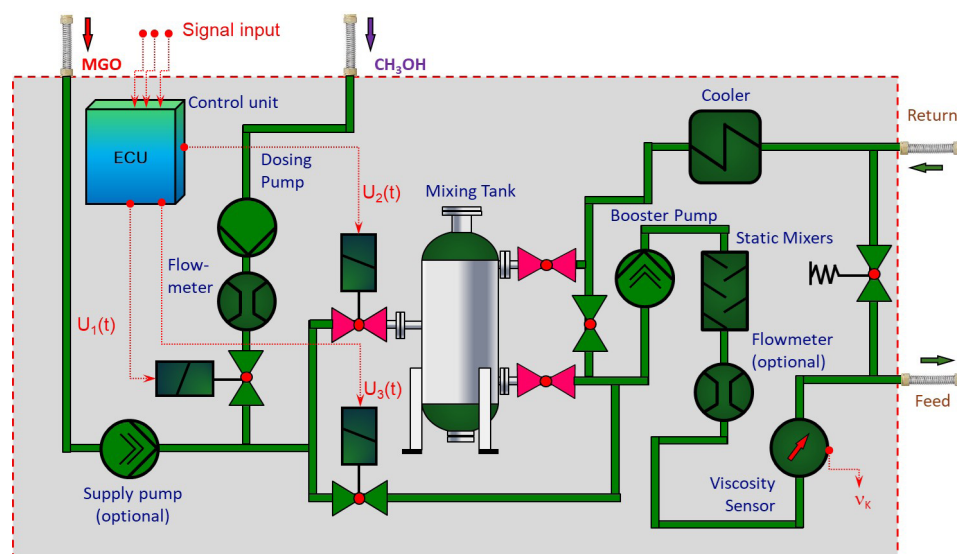
The module's developers shared the following results:

- The module has demonstrated stable performance with up to 30% alcohol when tested on a single-cylinder industrial engine and a medium-speed single-cylinder research engine. Alcohol ratios over 30% were found to create unstable combustion and were therefore excluded from recommended operating envelopes.²⁹

- Emissions studies demonstrated significantly reduced smoke, CO, and NO_x at medium to high loads.²⁹
- Material compatibility is critical for safety and reliability: for example, the use of alcohol-resistant elastomers, stainless steel fuel lines, and coated injector components.²⁹
- Flammability and toxicity risks are addressed via ATEX Zone 1 components, gas-tight A60 closures, ventilation and vapor detection, fire suppression systems, and automated fallback to diesel in case of abnormal conditions.
- The technology is currently advancing through a DNV Approval in Principle process following MSC.1/Circ.1621 and IGF Code guidelines.
- Next steps include an onboard pilot installation to test operational safety, reliability, and long-term engine compatibility, as well as comprehensive hazard identification (HAZID) and hazard and operability (HAZOP) assessments.

Additionally, one engine manufacturer has recently reported the incorporation of onboard blending technology for alcohol-diesel blends into its product portfolio.²⁰

Figure 2: Concept of an onboard alcohol-MGO blending module. Source: GenSys GmbH Wismar, used with permission.



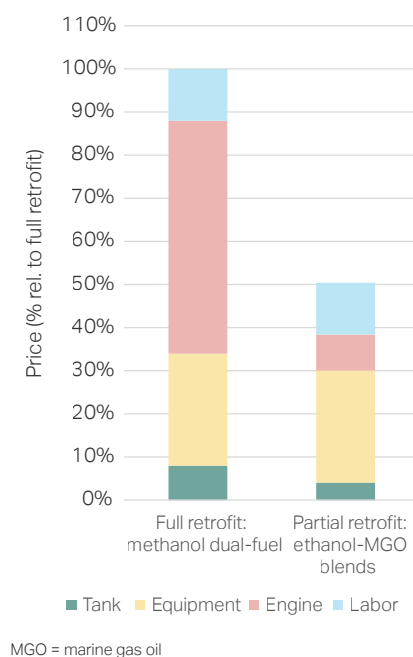
3.4 Techno-economic analysis of retrofit for operation on ethanol-MGO blends

To ensure onboard safety, operating a marine vessel using low-flashpoint fuels requires additional measures compared to operation on conventional marine fuels. Based on our research on ethanol-MGO blends shared in Sections 3.1 and 3.2, using these blends as fuel would require retrofitting to comply with SOLAS requirements. We therefore investigated the potential of such a retrofit based on a Kamsarmax bulk carrier with an approximate annual fuel consumption of 6,000 tonnes VLSFO-equivalent (tVLSFOeq). For the purposes of this analysis, all mentions of 'MGO' refer specifically to low-sulfur marine gas oil (LSMGO, $\leq 0.1\%$ sulfur content).

Drawing on a previous MMCZCS study,³⁰ we estimated that the cost of retrofitting the vessel to run on low-flashpoint ethanol-MGO blends (hereafter "ethanol-MGO retrofit") would be approximately 50% of the cost of retrofitting for full methanol dual-fuel capability ("full retrofit") (Figure 3). This is because retrofit of the main engine makes up almost half of the cost of the full retrofit. We assume that only part of this engine retrofit cost would apply to the ethanol-MGO retrofit.



Figure 3: Breakdown of modeled price for retrofit of a Kamsarmax bulk carrier for full methanol dual-fuel capability (left) versus ethanol-MGO capability (right).



The remaining estimated costs for the ethanol-MGO retrofit encompass equipment and modifications required for operation on low-flashpoint fuels, such as:

- Tanks suitable for carrying alcohols
- Double-walled piping
- Nitrogen generators
- Safety equipment
- Modifications to the fuel supply room
- Onboard fuel-blending equipment

However, the exact requirements and a more accurate cost estimate depend on the detailed vessel specifications and arrangement.

We next undertook a techno-economic analysis of operation on ethanol-MGO blends. We considered the following fuel options: ethanol-MGO blend, VLSFO, LSMGO, and FAME-VLSFO blend. Table 3 summarizes assumed fuel characteristics, including carbon intensity and prices.

Table 3: Fuel data assumptions for techno-economic analysis.

Fuel type	LCV (kJ/kg fuel)	WTW carbon factor (gCO ₂ eq/g fuel)	WTW carbon intensity (gCO ₂ eq/MJ)	Price (USD/tonne fuel)
VLSFO 0.5%S SIN	40,500	3.716	91.75	\$583
LSMGO 0.1%S SIN	42,700	3.876	90.77	\$663
Bio Bunker B30 (FAME-VLSFO 0.5%S SIN)	39,450	2.774	70.32	\$756
Ethanol T2 Europe	26,800	0.937	34.96	\$634
Ethanol B30 (Ethanol T2 Europe-LSMGO 0.1%S SIN)	37,920	2.992	78.91	\$654

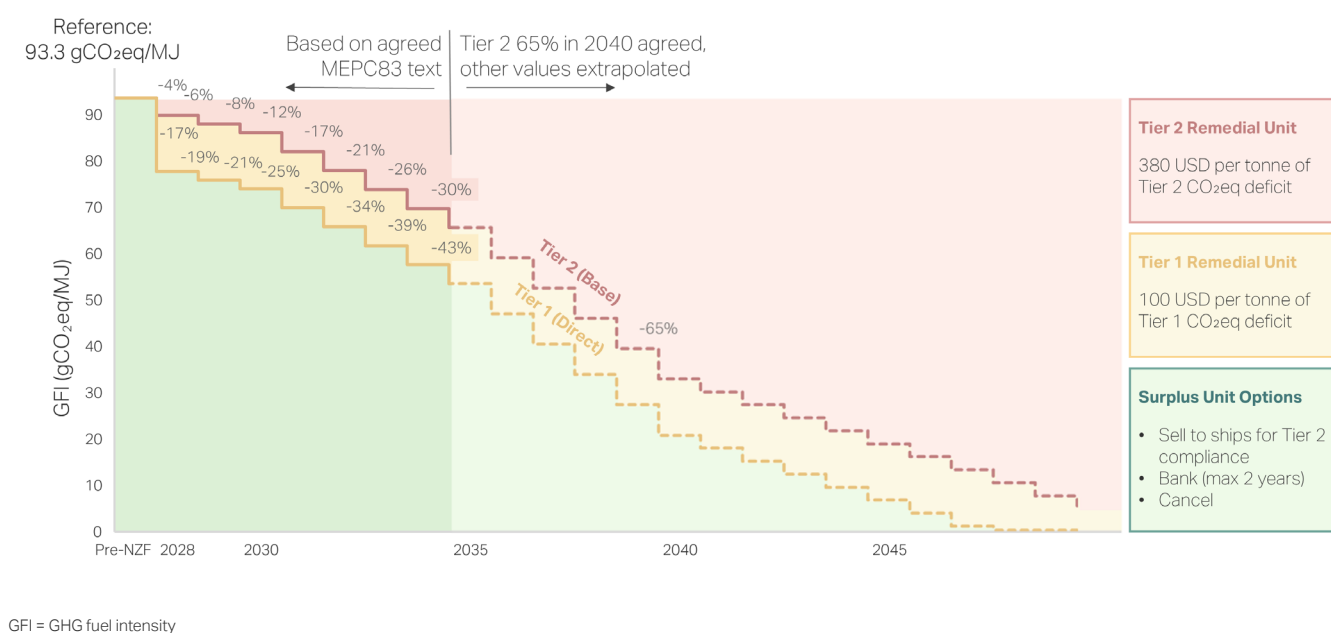
LCV = lower calorific value, WTW = well-to-wake, SIN = Singapore, VLSFO = very low-sulfur fuel oil, LSMGO = low-sulfur marine gas oil, FAME = fatty acid methyl ester

Notes: We considered emissions intensity (EI) default factors as per FuelEU Maritime for the fossil fuel pathways (VLSFO and LSMGO), an 85% EI reduction for FAME biodiesel, and a minimum 65% EI reduction for ethanol (corresponding to the default values from EU RED II).³¹ Fuel prices were taken as a long-term average for 2024 and 2025.³² Under FuelEU Maritime, ethanol originating from food/feed may be eligible for emissions reductions if produced according to the "carve-out" to food and feed stipulated by RED II, Definition (40).³¹ Our upcoming companion reports on GHG emissions intensity and techno-economic trends will indicate the range of the GHG emissions that these fuels may be associated with, as well as an approximate marginal cost of emissions reduction via some of these improvements.

We assumed a vessel lifetime of 25 years and that an ethanol-MGO retrofit would take place during dry-docking for the second special survey (vessel age 10 years). As ethanol is widely available, we did not consider specific trade routes or fuel availability.

Our modeling used a Tier 2 remedial unit (RU) price of 380 USD/tCO₂eq and a Tier 1 RU price of 100 USD/tCO₂eq, in line with the draft IMO Net-Zero Framework as proposed for adoption at MEPC 83.^{33,34}

We assumed that surplus units would be sold in a free market at the same price as Tier 2 RUs (380 USD/tCO₂eq) and did not consider any reward scheme for use of zero or near-zero emissions (ZNZ) fuels and energy sources. As the vessel's lifetime would extend beyond the time frame for which target GHG fuel intensity (GFI) values have been defined, we used extrapolated GFI target trajectories up to 2050 (Figure 4).

Figure 4: Assumed trajectory for emissions reduction targets under the IMO NZF.³⁴

Using these assumptions, we compared the net present-value total cost of ownership (TCO) of existing fuel pathways (VLSFO, LSMGO, and FAME-VLSFO blend) to the ethanol-MGO retrofit solution. We studied the sensitivity of this TCO to the price and carbon intensity of ethanol (Figures 5-8) using the baseline parameters in Table 4.

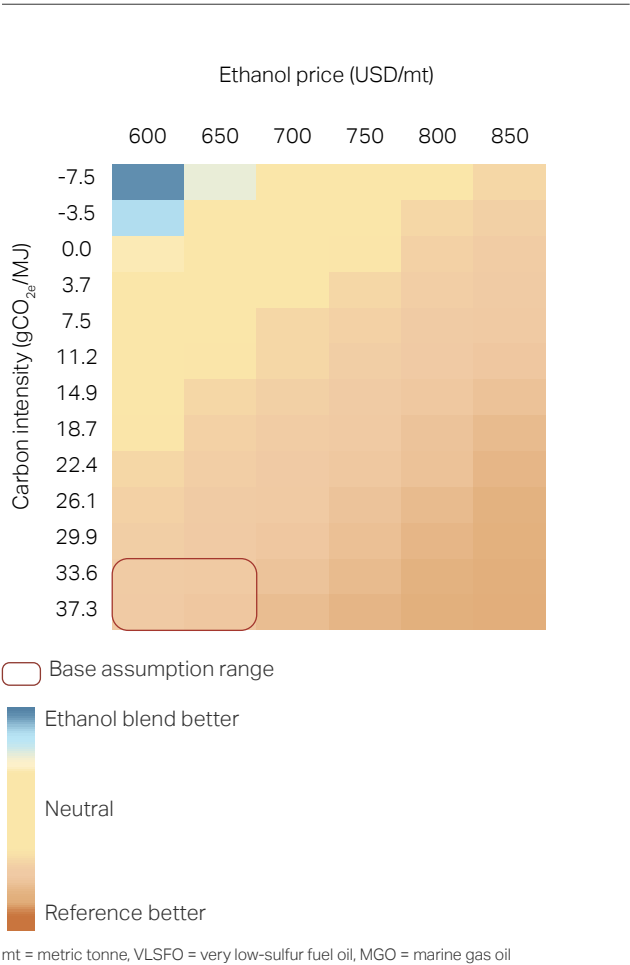
Table 4: Baseline parameters for sensitivity analysis of total cost of ownership.

Expected annual VLSFO consumption	6,000 mt
Retrofit investment CapEx	50% of cost for full dual-fuel retrofit ³⁰
Discount rate	7%
Ethanol blend ratio (mass)	30%

VLSFO = very low-sulfur fuel oil, CapEx = capital expenditure, mt =metric tonnes, DF = dual-fuel

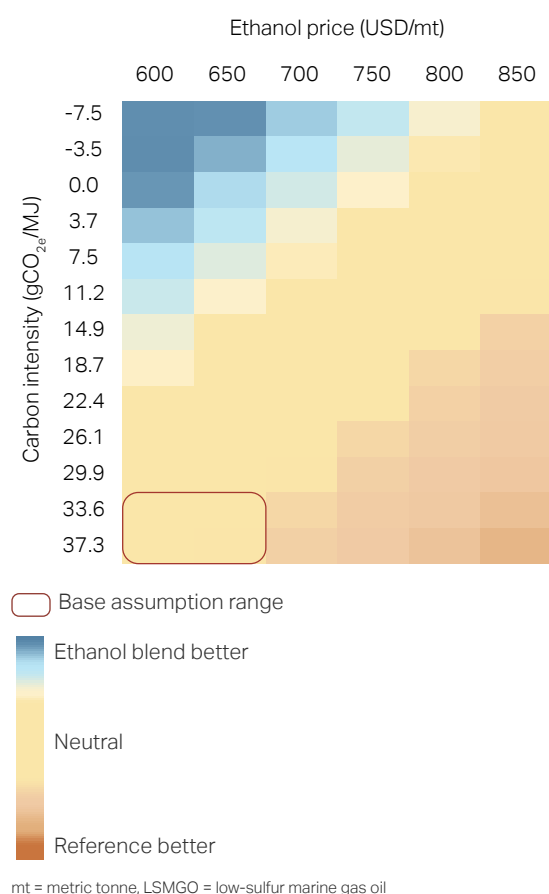
Under our baseline assumptions for fuel prices, carbon intensity, and retrofitting cost, the ethanol-MGO retrofit does not offer an improved TCO compared to operation on VLSFO (Figure 5). However, Figure 5 also shows that the retrofit could be commercially viable if the vessel has access to ethanol produced with a low carbon intensity, even if the ethanol price is slightly higher than the baseline.

Figure 5: Sensitivity of total cost of ownership to price and carbon intensity of ethanol – comparing VLSFO with ethanol-MGO retrofit.



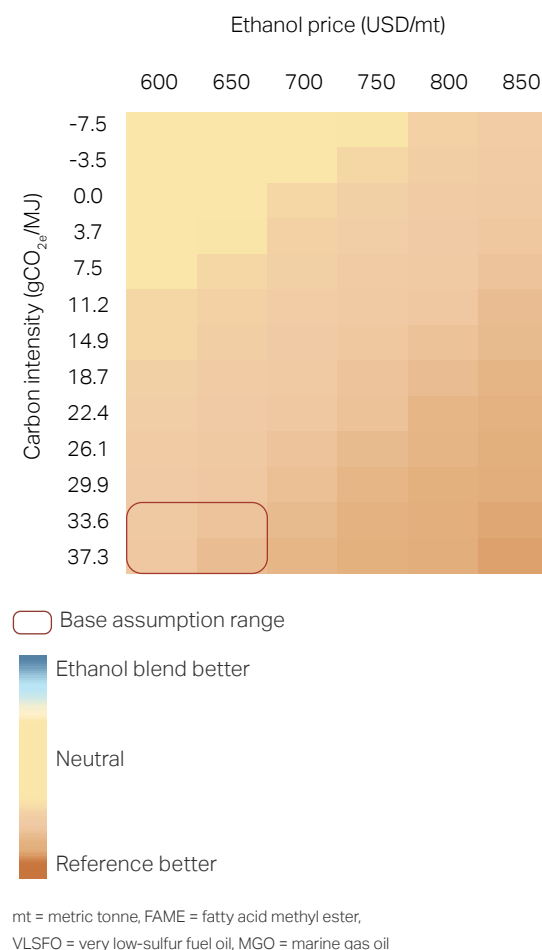
To model a case where the vessel predominantly operates in a sulfur emissions control area (SECA), we used LSMGO rather than VLSFO as the reference for conventional maritime fuel. In this case, retrofitting the vessel to operation on low-flashpoint ethanol-LSMGO blends is commercially attractive for a range of fuel prices and carbon intensities (Figure 6).

Figure 6: Sensitivity of total cost of ownership to price and carbon intensity of ethanol – comparing LSMGO with ethanol-MGO retrofit.



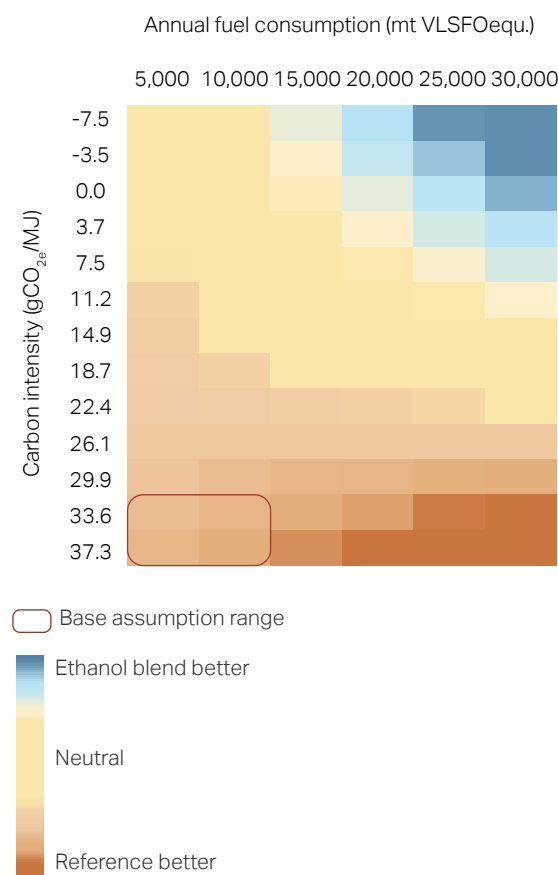
We also compared the retrofit option to operation on a FAME-VLSFO blend, a lower-emissions option that can be used without vessel modifications. In this case, the ethanol-MGO retrofit is only commercially viable when ethanol has a very low fuel price **and** low carbon intensity (Figure 7).

Figure 7: Sensitivity of total cost of ownership to price and carbon intensity of ethanol – comparing B30 FAME-VLSFO blend with ethanol-MGO retrofit.



Finally, we investigated the impact of vessel size/type on the TCO by modeling sensitivity to annual fuel consumption. Higher annual fuel consumption meaningfully improves the retrofit business case (Figure 8). These results suggest that a vessel with an annual fuel consumption of 25,000 tonnes (e.g., a large container ship) could economically operate on a 30:70 ethanol-MGO blend for a wide range of ethanol carbon intensities. This finding also holds if the vessel operates on fuel blends with higher proportions of ethanol, but not if the ethanol share drops below 30%.

Figure 8: Sensitivity of total cost of ownership to annual fuel consumption and ethanol carbon intensity – comparing VLSFO with ethanol-MGO retrofit.



mt = metric tonne, VLSFO = very low-sulfur fuel oil, MGO = marine gas oil

In summary, our analysis suggests that an ethanol-MGO retrofit could be a viable option for some vessels operating in SECAs and/or with access to ethanol with low carbon intensity – assuming that emissions intensity thresholds and compliance mechanisms as per draft IMO NZF are in place. The retrofit option appears to be more economical for vessels with higher annual fuel consumption.

Factors that could increase the viability of an ethanol-MGO retrofit, based on sensitivity analysis modeling:

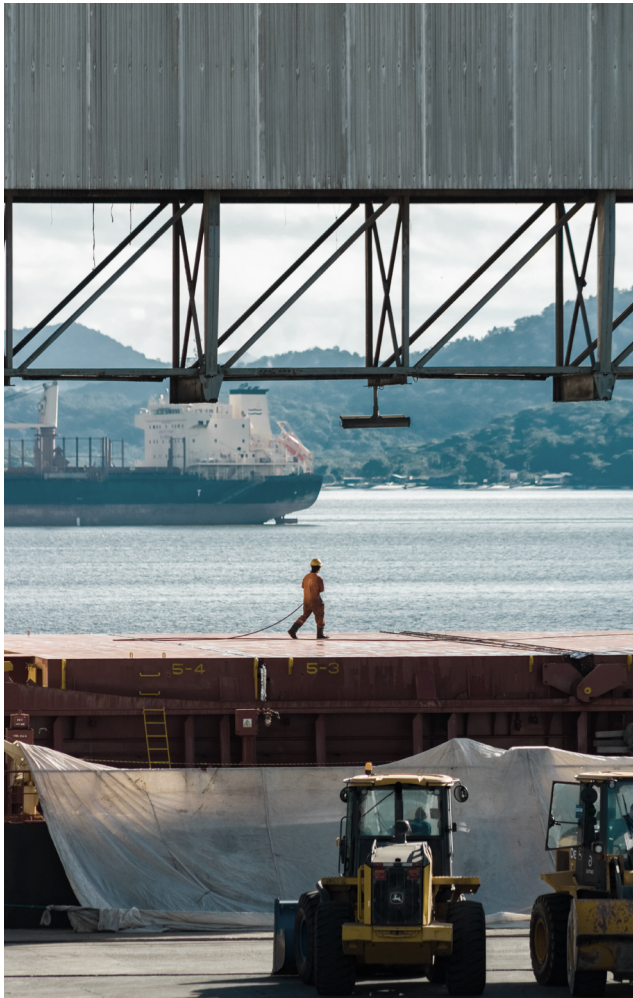
- ↑ Increased reference fuel price
- ↓ Decreased retrofit CapEx
- ↑ Increased fuel consumption
- ↓ Decreased emissions intensity of ethanol
- ↓ Decreased ethanol price
- ↑ Increased regulatory penalties for greenhouse gas emissions
- ↑ Increased time in SECAs

For vessels operating within the European Union (EU), the FuelEU Maritime regulation could change the results of the techno-economic assessment. The draft IMO NZF and FuelEU differ in their emissions-reduction trajectories and the costs associated with non-compliance. Since considering the FuelEU adds more cases and complexity to the techno-economic assessment, we opted to undertake a qualitative assessment for the purposes of this report.

Operation on non-compliant fuel results in broadly similar compliance costs under both regulatory frameworks for extra-EU voyages (i.e., where one port of call is in the EU territory and the other outside). When a voyage falls fully within the scope of FuelEU Maritime (i.e., both ports of call are in EU territory), the cost of compliance becomes significantly higher under FuelEU Maritime. This implies a stronger business case for the ethanol-MGO retrofit. However, vessels would need to be continuously employed in intra-EU trade to fully capture this benefit. Considering that larger vessels predominantly operate in international trades, this factor likely limits the number of vessels that could harness the compliance benefits of FuelEU to make a business case for the retrofit.

04 Key topics for further consideration

Operating vessels on ethanol-MGO blends introduces fundamentally higher risks of fire and explosion compared with conventional marine fuel systems. As such, it will be essential to carry out HAZID and HAZOP and obtain class approval before testing a first demonstrator installation of this fuel blend. Structured hazard identification and risk assessment ensure that all credible failure scenarios are systematically identified, mitigated, and engineered out where possible. Meanwhile, class approval independently verifies that the design, equipment, and test arrangements comply with applicable rules and international safety standards. This protects personnel, assets, and the environment, while safeguarding regulatory acceptance and insurability of the technology.



Future technical work could include assessing the feasibility of ethanol-VLSFO blends for retrofit applications, similar to that presented for ethanol-MGO blends in this report. If feasible, these applications could unlock commercial advantages by allowing ethanol-assisted combustion both inside and outside SECAs. This assessment should include:

- Whether emulsifiers or biodiesel can enhance ethanol's solubility in VLSFO
- Whether onboard, on-demand blending systems could enable stable ethanol-VLSFO operation

Our assessment of the cost of retrofit for operation on ethanol-MGO blends was preliminary. Developing a technology that ensures safe handling of blends at an affordable price might be interesting for OEMs.

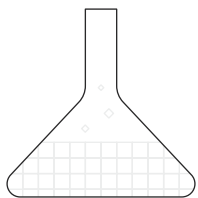
Finally, a detailed assessment of the business case for ethanol-MGO blends under the FuelEU Maritime regulation would be a worthwhile topic for future work. This type of assessment was outside the scope of this report.

05 Conclusion



Ethanol is a promising drop-in option for methanol-fueled vessels

Ethanol is emerging as a technically viable complementary fuel within the methanol pathway, supported by growing evidence that methanol dual-fuel engines can operate on ethanol with only limited adjustments. Ethanol's combustion behavior, emissions profile, and material compatibility closely mirror those of methanol, while ethanol's higher energy density reduces onboard storage needs. Remaining technical challenges mainly relate to optimization and emissions certification, as engines must demonstrate compliance using each fuel separately. As low-emissions methanol production and supply scale up, ethanol could play a practical role in enhancing fuel flexibility and reducing supply chain risks. With that said, these conclusions reflect technical performance only – sustainability and affordability will be addressed in other reports in this series.



Blending ethanol with conventional marine fuels requires new technical solutions

Meanwhile, ethanol-MGO blends present a potential emissions reduction pathway for the existing diesel fleet. However, the practical use of these blends is challenged by fundamental fuel properties. In our testing, adding even a small proportion of ethanol to MGO reduced the blend's flashpoint to below SOLAS requirements, and we were unable to raise the flashpoint to compliant levels using biodiesel or α -terpineol. With that said, a partial vessel retrofit to accommodate the fuel's low flashpoint offers a path forward to enabling operation of existing vessels on ethanol-MGO blends.

Further research may reveal other solutions that could make ethanol a 'true drop-in' fuel for conventional engines.

In addition, the ethanol-MGO blends we tested showed consistent phase separation, especially when stored for longer periods or at lower temperatures. As such, onboard blending technologies could offer a more practical alternative to pre-mixed blends. Developers of an onboard blending solution have reported successful early tests with stable operation on up to 30% ethanol in MGO. The technology is now progressing through class approval and a planned pilot installation.

Partial retrofit to enable operation on ethanol blends may be an attractive emissions reduction pathway for some existing vessels



We carried out a techno-economic assessment to understand the business case for a partial retrofit that allows a Kamsarmax bulk carrier to operate on ethanol-MGO blends. We estimated that the cost of this retrofit would be approximately half that of a retrofit to full methanol dual-fuel operation. Under our assumptions, the ethanol-MGO retrofit becomes commercially attractive under specific conditions such as SECA-dominated operations, access to low-carbon ethanol, or high annual fuel consumption. Compared with the draft IMO NZF, the FuelEU Maritime framework offers higher incentives for intra-EU voyages while limiting the applicable fleet segment. Overall, our initial results suggest that retrofitting to ethanol-MGO operation could be a meaningful decarbonization option for some existing vessels.

06 Acknowledgements

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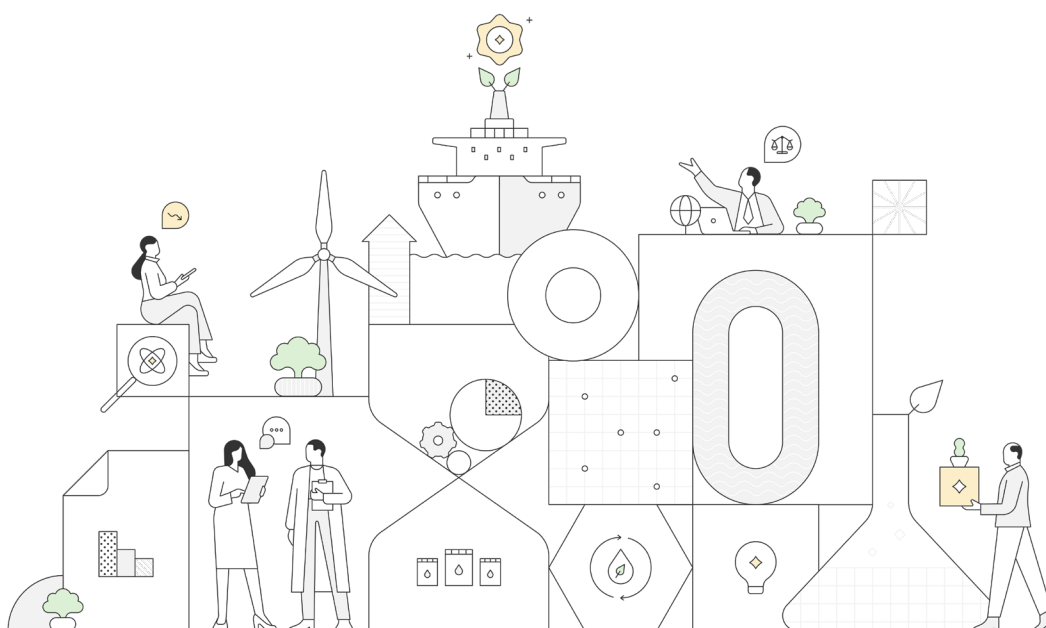
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Abbreviations

CapEx	Capital expenditure
CIMAC	Conseil International des Machines à Combustion
CO	Carbon monoxide
EI	Emissions intensity
EU	European Union
FAME	Fatty acid methyl esters
GFI	Greenhouse gas fuel intensity
GHG	Greenhouse gas
HAZID	Hazard identification
HAZOP	Hazard and operability
IGF Code	International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels
IMO	International Maritime Organization
IMO NZF	IMO Net-Zero Framework
ISO	International Organization for Standardization
LSMGO	Low-sulfur marine gas oil
MGO	Marine gas oil
MMMCZCS	Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping
NO _x	Nitrogen oxides
OEM	Original equipment manufacturer
RU	Remedial unit
SECA	Sulfur emissions control area
SOLAS	International Convention for the Safety of Life at Sea
TCO	Total cost of ownership
tCO ₂ eq	Tonnes CO ₂ equivalent
tVLSFOeq	Tonnes very low-sulfur fuel oil equivalent
USD	United States dollars
VLSFO	Very low-sulfur fuel oil
ZNZ	Zero or near-zero emissions fuels and energy sources

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