APRIL 2025

DUAL-FUEL SOLUTIONS FOR NEWBUILD VESSELS

TECHNICAL AND OPERATIONAL ADVISORY

ABS

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EXECUTIVE SUMMARY

The maritime industry faces increasing regulatory pressure to decarbonize, driven by the International Maritime Organization (IMO) emission reduction targets and the European Union (EU) maritime emission regulations. Shipowners are exploring different dual-fuel (DF) propulsion options as a pathway to reduce greenhouse gas (GHG) emissions and to support future-proofing their assets against upcoming regulations.

This advisory provides a comprehensive examination of DF propulsion options for a newbuild vessel. These DF solutions typically include traditional hydrocarbon-based fuel and an alternative fuel (such as liquefied natural gas [LNG], liquefied petroleum gas [LPG], methanol, etc.). This publication will focus on LNG, methanol and ammonia as potential alternative fuels only, as alternatives such as LPG and ethane are considered specialized (for LPG and ethane carriers respectively) short-term solutions, as green alternatives for these fuels are not expected to be developed.

OVERALL CONSIDERATIONS

FUEL OPTIONS

LNG

It is currently the most mature fuel solution; offering significant emissions reductions compared to conventional marine fuels. In addition, biogas (BioLNG) has the same chemical composition as LNG and is a drop-in fuel in LNG systems. However, challenges include the complexity of fuel containment systems, high costs, and methane slip, which could limit long-term compliance with stringent emissions regulations. In the short term, using a green version of LNG (biogas or synthetic LNG) for LNG carriers will be more challenging because they usually burn the cargo they carry.

CH_3OH

Methanol

Methanol is emerging as a viable alternative for the marine industry due to its lower carbon footprint and simpler onboard handling. Similarly to LNG, the green versions of methanol (biomethanol and synthetic methanol) can easily be used as drop-in fuels in methanol systems. The existing infrastructure for methanol bunkering (based on its wide use in the chemical industry and the large volume shipped around the world) is a benefit, but its lower energy density and high flammability require careful management and additional safety measures.

NH_3

Ammonia

Ammonia is a promising carbon-free fuel, but its adoption faces significant hurdles related to toxicity and handling. Despite these challenges, ammonia's potential for near-zero emissions makes it a key contender for future-proofing against ever more stringent GHG reduction regulations. Green ammonia can be produced without the need for biogenic carbon. This is a significant advantage compared to the other fuels. Similarly to LNG and methanol, blue and green ammonia is a drop-in fuel for ammonia systems on board ship.

REGULATORY LANDSCAPE

The industry is transitioning from conventional Tank-to-Wake (TtW) emissions evaluations to a Well-to-Wake (WtW) approach, accounting for the entire life-cycle emissions of fuels. This shift demands that shipowners consider alternative fuels that can meet both current and future regulatory standards, such as the IMO's Revised Strategy and the relevant elements of EU's Fit for 55 legislative package (e.g., EU Emission Trading Scheme (EU ETS), FuelEU Maritime, etc.).

ECONOMIC AND OPERATIONAL IMPLICATIONS

Economic analysis suggests that while DF LNG and DF methanol vessels have higher initial investment costs, they offer varying levels of regulatory compliance and operational cost savings over time. Ammonia, though currently less developed, could provide substantial long-term compliance benefits due to its near-zero GHG emissions potential.

The choice of fuel impacts not only the design and construction of vessels but also their operational efficiency, safety and long-term viability in a decarbonizing industry.

The key decision factors that shipowners should consider are:

- **Fuel Infrastructure Availability:** Is the supply chain ready to support the fuel choice?
- **Regulatory Compliance:** How does the fuel align with evolving IMO and EU requirements?
- **Operational Impact:** What are the implications for vessel range, efficiency and safety?
- **Economic Feasibility:** What are the upfront costs vs. long-term savings?

KEY POINTS TO CONSIDER

BASIC DESIGN CONSIDERATIONS

Fuel Containment Systems

Determine the most suitable fuel containment system (Type A, B, C or membrane for LNG; appropriate tanks for methanol and ammonia) based on vessel design, space availability and operational profile. Consider the implications of tank type on safety, cost and operational complexity.

Fuel Supply Systems (FSS)

Specify the design requirements for the FSS, considering the need for redundancy, pressure management and compatibility with the selected fuel. Investigate the integration of safety measures such as double-walled piping, inert gas systems and appropriate venting solutions.

Machinery Space Concept

The non-hazardous machinery space concept should be chosen to minimize complexity and cost, especially considering the high toxicity of ammonia.

WHERE TO PAY ATTENTION

Safety Considerations

Focus on the safety systems associated with each fuel, such as gas detection, fire suppression and emergency shutdown systems. Pay special attention to the design of machinery spaces, bunkering stations and ventilation systems to comply with the International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code) and the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code).

Corrosion and Material Compatibility

For methanol and ammonia, all materials in contact with these fuels are to be resistant to corrosion. Specify the use of stainless steel, special coatings or compatible non-metallic materials where necessary.

Machinery Space Concept

The design should facilitate efficient and safe bunkering operations, considering the need for vapor return systems, pressure control and compatibility with bunker vessels. Evaluate the implications of bunkering on operational schedules and routes.

WHAT TO LOOK FOR

- **Regulatory Compliance:** The vessel's design and fuel systems meet the latest IMO and EU regulatory requirements, particularly regarding GHG emissions and safety. An important element is the gradual shift to WtW emissions which highlights the need to consider the selection of the fuel under the life-cycle perspective.
- **Operational Impact:** Assess the impact of the selected DF system on the vessel's operational efficiency, including fuel availability, infrastructure readiness, availability of skilled crew and the potential for reduced cargo capacity due to larger fuel tanks.
- **Technology Maturity:** Examine the technological readiness level of each fuel option. Liquefied natural gas is the most mature, methanol use in main engines, FSS and tanks are mature as well, while ammonia presents emerging but less proven alternatives. The first ammonia-fueled oceangoing ship will be going into service around the beginning of 2026. Evaluate the reliability and service experience of engines and FSS for each fuel.

CONCLUSION

Choosing the right DF propulsion system for a newbuild vessel requires balancing:

- Future regulatory compliance (EU ETS, FuelEU Maritime, IMO GHG Fuel Standard [GFS])
- Fuel availability and infrastructure readiness
- Operational flexibility and safety considerations
- Long-term economic viability

Liquefied natural gas offers immediate benefits due to its maturity and established infrastructure, with methanol and ammonia presenting promising alternatives with distinct challenges related to safety and handling, while offering greater compliance flexibility and sustainability in the long run. Each fuel option carries its own set of challenges and advantages, and the optimal choice will depend on specific operational profiles, regulatory environments and the owner's long-term strategic goals.

INTRODUCTION

ABS is committed to being a recognized leader for new technology development and assessment, and for serving as a trusted technical advisor to the marine industry. These pillars have formed the foundation for the success of ABS for more than 160 years, and, more importantly, position the organization to provide the practical solutions needed for the future. Positioned around the world, the ABS team has the experience, knowledge and professional judgment to assist our members and clients in developing their marine projects worldwide.

Spurred by the International Maritime Organization's (IMO) emissions reduction targets, and European Union (EU) maritime emissions regulations, the industry continues to face increased pressure to decarbonize, creating new challenges across the maritime value chain. Ship emissions have become an increasingly important factor to vessel owners, both air emissions and discharges to the sea. The mounting regulatory pressure combined with charterers making decisions regarding which vessels to charter and ports providing incentives for cleaner vessels has led to the need for more involved solutions for reducing emissions.

Traditionally, only Tank-to-Wake (TtW) emissions, the emissions generated on board the vessel from the combustion of the fuel, were considered. This is no longer the case, with upcoming regulations such as the FuelEU Maritime and the IMO greenhouse gas (GHG) Fuel Standard (GFS) considering the full life cycle of the fuel, that is, both fuel production emissions Well-to-Tank (WtT) and shipboard combustion TtW emissions, the Well-to-Wake (WtW) approach.

To satisfy these regulations, conventional improvement options, such as low-friction coatings, propulsion improvement devices and machinery efficiency improvements will no longer be sufficient. A change of fuel is one of the solutions that must be considered.

This advisory outlines the key factors requiring attention when considering dual-fuel (DF) vessels. These include design aspects (usually reflected in a new build specification), critical aspects relating to the selection of the DF engine and operational aspects that require consideration. In addition, regulatory and economic considerations are also presented.

NEWBUILD SPECIFICATION

Applying alternative fuels in newbuild vessels offers significant benefits for reducing emissions but also introduces specific challenges. The adoption of alternative fuels requires a solid understanding of the associated risks, not only for vessel safety but also for the safety of all personnel involved in the ship's operations.

The following sections will focus on implementation of liquefied natural gas (LNG), methanol and ammonia as marine fuel for newbuilds from a technical perspective. However, it is important to highlight that the success of these efforts depends on the workforce's expertise in handling these fuels. Crew members must be qualified and certified for working on board vessels using alternative fuels. Therefore, training programs must continuously evolve to keep up with technological advancements and regulatory updates.

The main challenges and characteristics associated with each fuel include:

- Flammability and explosion risks
- Toxicity
- Material compatibility, reactive and corrosive behaviors
- Environmental impact
- Specific fuel properties (lower calorific value [LCV], energy density...)

Table 1 provides an overview of the basic fuel properties in comparison with the conventional option of marine gas oil (MGO).

Fuel	Boiling Point (° C) at 1 bar(a)	Liquid Density (kg/m³)	LCV (MJ/kg)	Flammable Range (% vol in air)	Energy Density (MJ/L)	Volume Comparison with MGO
MGO	360	85	45.9	1-8	39.2	1
LNG	-163	428	48.6	5-15	20.6	~1.9
Methanol	65	790	19.9	6-36	15.7	~2.5
Ammonia	-33	682	18.8	15-28	12.8	~3.1

Table 1: Fuel properties.

Liquefied natural gas is currently used as fuel across various types of vessels. Extensive experience deriving from LNG carriers and LNG bunkering infrastructure has reached a level of maturity with numerous LNG bunker vessels operating worldwide. Technology, especially regarding containment systems and engines, is also mature, having been developed and refined over the years. Challenges associated with LNG include the complexity of some containment systems, fuel gas supply systems (FGSS) and the effective management of high levels of boil-off gas (BOG).

Methanol is a widely shipped chemical, and there is experience with transportation on ships as cargo and available infrastructure that can easily be developed to support bunkering ships. Methanol engines, developed by major manufacturers, have demonstrated proven reliability in operation. Methanol is a liquid in ambient conditions, making handling and onboard containment much simpler than LNG or other liquefied gaseous fuels. If mishandled, methanol can be toxic, with the potential to cause serious health issues such as blindness or death if ingested. Its toxicity is critical not only through ingestion but also via inhalation or skin contact. It is a highly flammable liquid with a large flammability range (6 to 36 percent volume in air), low flashpoint (11° C) and high heat of vaporization. Methanol-water mixture with over 25 percent can still be flammable. Methanol flames are nearly invisible without producing smoke and can be undetected at initial stages. Methanol causes corrosion; therefore, carbon steels need a special coating to be protected or stainless steel to be used. Non-metallic materials used in fuel tanks and pipes are to consist of appropriate methanol-compatible materials, such as nylon, neoprene or non-butyl rubber.

Ammonia is a promising fuel due to its carbon-free compound. However, due to toxicity, it poses serious health risks at low concentrations and can be fatal at higher levels if not properly handled. Given its high toxicity to aquatic life, spills may significantly affect the marine ecosystem. The severity of these impacts depends on factors such as concentration and duration of the spill, as well as water temperature, pH, and salinity. It is readily soluble in water, where it acts as a base forming the ammonium ion NH_4+, which is less harmful to organisms compared to ammonia. The ratio of NH_4+ and ammonia in water depends on temperature, salinity and pH level. In open seawater, ammonia will evaporate from the upper layers of the water column and will not affect the lower water column layers. Recent studies show that ammonia may cause adverse effects, including death, to sensitive species or individual organisms in an open sea during the first day after the spill. Thereafter, the sea environment starts to recover.

Due to its pungent smell, ammonia can be detected well below 25 parts per million (ppm), which is an early warning signal. Introducing this toxic fuel presents new challenges related to safe bunkering, storage, supply and consumption. A ship's design is affected, as the release of ammonia should be mitigated in all cases. Toxic areas should be determined upon an ammonia gas dispersion analysis.

While less likely to ignite in open air due to its flammable range (15 to 28 percent volume in air) and rapid diffusion, ammonia presents a significant ignition risk in confined spaces, especially in the presence of oil and other combustibles. Storage tanks may also be at risk of explosion under high heat.

Ammonia requires refrigeration at -33° C to remain a liquid at atmospheric pressure. Exposure to higher temperatures can lead to brittle fractures in containment materials and frostbite risks from evaporating ammonia.

Ammonia's reaction with various materials can lead to significant integrity issues. It should not contact mercury, copper, copper-bearing alloys and zinc to avoid corrosion. Interaction with carbon dioxide (CO_2) can form carbamates, leading to clogs and damage in the fuel system. Oxygen presence can accelerate stress corrosion cracking in steels at high temperatures.

DF LNG VESSEL

When considering the design of LNG-fueled ships, several systems need to be integrated into the vessel that are different, or additional, to conventional ship designs. These include the LNG fuel containment system, LNG bunker station and transfer piping, FGSS, the double-wall fuel gas distribution piping, gas valve unit (GVU), gas consumers, nitrogen generating plant, vent piping systems and mast(s), and depending on the LNG tank type, additional equipment for managing tank temperatures and pressure.

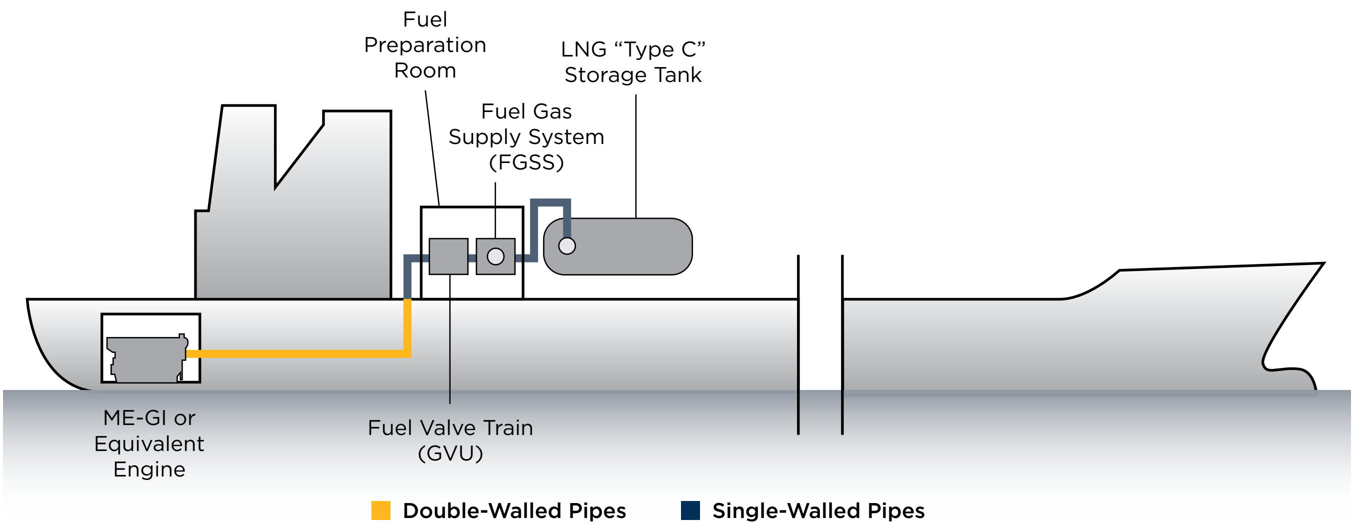


Figure 1: Installations on board new-build DF LNG ship.

The protective LNG tank location criteria can be based on a deterministic approach considering tank volume or a probabilistic method. The International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels (IGF Code) provides a third alternative, where the ship’s hull is specifically designed and reinforced in the way of the LNG tank, therefore minimizing the impact from a collision and allowing the tank to be closer to the ship’s side shell.

FUEL CONTAINMENT

There are four main types of LNG tanks: independent tank types A, B and C, and integrated membrane tanks. Types A, B and membrane are low-pressure, nominally atmospheric tanks, whereas Type C are pressurized tanks. Type A, B and membrane tanks require a secondary barrier for protection in case of a leak from the primary barrier. Type A and membrane systems require a full secondary barrier. Type B requires a partial secondary barrier since these are designed using advanced fatigue analysis tools and a leak before failure concept, for which small leaks can be managed with partial cryogenic barrier protection and inert gas management of the interbarrier space. Type C tanks are designed using pressure vessel code criteria and conservative stress limits. Therefore, they do not require a secondary barrier.

Most gas fueled ships in operation have the IMO Type C pressurized fuel tanks. This is because these are relatively inexpensive to manufacture and simple compared to the other fuel containment types, particularly in the smaller sizes required by the current gas fueled fleet. Type C tanks can also simplify the required BOG management equipment because of their pressure accumulation capability. However, these tanks might not be the most space-efficient option.

The LNG fuel containment system selected will influence the installed equipment for BOG management and also have an operational impact on tank filling levels and how bunkering (tank pressure and vapor return) is managed in service. The complexity of LNG bunker vessels is greater than conventional fuel oil bunker vessels and introduces specific compatibility challenges.

The IGF Code permits a number of ways to manage BOG, including consumption, reliquefication, cooling and pressure accumulation. The IGF Code sets criteria for monitoring and managing tank pressure and temperature at all times and for maintaining tank pressure below the relief valve setting for 15 days when the vessel is idle with domestic load only. The 15-day criteria may be difficult for atmospheric tanks to achieve on domestic (hotel) load only. Therefore, they may necessitate the fitting of additional BOG management equipment, such as reliquefication systems or gas combustion units.

Large deep-sea vessels would likely specify membrane fuel containment systems or Type B tanks to limit the loss of cargo space compared to conventional fueled ships. However, for large containerships, Type C tanks have shown to be the cheapest, even considering the loss of containers. Sloshing can be an issue that requires special consideration for membrane tanks. Liquefied natural gas membrane tanks for GFS need to be designed to accommodate all LNG liquid levels as in service. Therefore, the tanks will be designed with higher density insulation materials and membrane reinforcement in critical areas.

FUEL GAS SUPPLY SYSTEMS

The purpose of the FGSS is to deliver fuel to the engine or consumer at the required temperature and pressure. For gaseous fuels using cryogenic/pressurized liquefied storage, the fuel may be pumped or pressure fed directly in liquid forms, such as LNG, from the tank and vaporized to a gaseous state for the consumer or supplied in combination with the use of compressed gas from the natural tank BOG.

For GFS, the amount of BOG available in certain instances might not be sufficient to sustain the ship's power demands at maximum continuous rating (MCR), so the FGSS must force the vaporization of LNG into conditions suitable for the engines. In some cases, the designers may prefer to force the LNG to vaporize and send it to the main engines because it could be cheaper and more efficient to boost pressure on LNG and vaporize it on a high-pressure vaporizer rather than use a compressor. However, the ship will always still need to manage the BOG and LNG tank pressures, including times when there is no gas consumption by propulsion-related consumers, which can lead to many potential combinations for fuel supply and BOG management equipment.

ENGINES

For DF engines, typically there is no requirement for FGSS redundancy since the basic safety concept is that the primary fuel remains the fuel oil and seamless transition back to oil mode is required in the event of a safety system trip of the gas fuel system. In those cases where gas is the means of Tier III nitrogen oxide (NO_x) compliance, the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI/NO_x Technical Code (NTC) permits transit to the next port in Tier II mode. However, for practical reasons, duplication of rotating and reciprocating FGSS equipment, such as submerged LNG pumps or high-pressure cryogenic pumps, is often specified by shipowners and operators for redundancy, reliability and maintenance purposes.

Two common engine and FGSS options are:

1. High-pressure DF engine operating on Diesel Cycle where the gas is supplied to this engine at high pressure (300 bar). Therefore, the FGSS involves high-pressure pumps, evaporators and high-pressure compressors.
2. Low-pressure DF engine operating on Otto (gas mode) and Diesel Cycle (fuel mode) where the gas is supplied to the engine at low pressure (6 to 13 bar).Therefore, the FGSS involves low-pressure pumps, evaporators and low-pressure compressors.

Common issues reported so far involve the main engines and the relevant FGSS. However, this is to be expected as these technologies are relatively new to the marine industry. The problems reported on high- and low-pressure engines primarily involve components related to gas mode operation. Based on the collected service experience, engine designers have improved their designs to minimize operational issues. Problems were initially reported with FGSS operation. However, the suppliers of this equipment have also developed and further improved the designs to eliminate operational issues. The crew's level of experience is very important. Containing natural gas in the system is still a big issue for less experienced crews. A small gas leak will result in a gas stop and a return to fuel oil operation. Normally, there are no built-in redundancies in the gas system, so maintaining the system and avoiding gas leaks to keep a high uptime on gas fuel use requires skilled engineers. Overall, the development process of DF engines and FGSS is still ongoing. Four-stroke auxiliary LNG DF generators are also available on the market, enabling a vessel to be fully LNG fueled.

BUNKERING

Suppose the trading route is known during the design stage, and the potential bunker supplier along the path is identified. In that case, measures/contracts can be established so that the parameters of the LNG vessel during bunkering and the supplier/bunker vessel are aligned and the bunkering procedures standardized. If trading routes and suppliers are unknown during the design stage, then it might be beneficial to increase the equipment limits on the ship so that issues arising from bunkering are handled correctly. Vapor return needs to be considered during the design when the bunker supplier can receive and handle vapor return. Vapor return assists with reducing heat transfer while loading the LNG tank with liquid from the bottom in lieu of using top spray to manage pressure accumulation. Additionally, vapor return assists with reducing the duration of the bunker evolution since liquid can be filled in the bottom of the tank, and any vapor pressure accumulated during loading can be returned to the supplier.

The temperature of bunkers and pressure control are two issues of concern.

- The colder the LNG is from the LNG supplier, the better it is for the GFS. This means there is more time to manage pressure control in the tanks. If the bunker vessel supplies warm LNG, this might result in handling increased boil-off/pressure, which may lead to an increase in fuel consumption just to handle the pressure.
- Linked to temperature, an additional concern is understanding if the LNG gas carriers/bunker vessel's vapor return system has been evaluated for conducting vapor balancing in a compatibility study/assessment with the gas-fueled vessel. Vapor balancing design compatibility between supplier and receiver must be verified. As we look at larger bunker tanks, an owner needs to consider what happens during the cooldown of the bunker tank prior to full rate loading and how to handle the associated flash gas that will be generated. If this is not considered, it will impact the duration of the bunkering operation evolution, which in turn may impact the expected operating profile.

In addition to verifying the vapor balancing design compatibility between supplier and receiver, there could be challenges with documenting custody transfers. In addition to measuring quantities of LNG supplied to the GFS, the amount of vapor returned may need to be measured. Credits for gas vapor return need to be included in the overall price during custody transfer.

Other areas, such as bunker station location and bunker vessel compatibility, are to be considered. Issues may arise if the location of the bunker station is such that the hazardous area from the bunker vessel overlaps areas where the crew (or passengers) are located.

SAFETY CONSIDERATIONS

Two machinery space concepts are included in the IGF Code (i.e., non-hazardous and emergency shutdown (ESD) machinery space). The ESD machinery space concept introduces additional measures to provide an equivalent level of safety to the conventional non-hazardous machinery space. The application of the ESD machinery space has been limited so far because of the growing availability of engines that can be supplied to meet the double barrier criteria and perhaps because of the additional vessel complexity and cost that meeting the ESD machinery space concept brings. The non-hazardous machinery space concept is based on the use of double barriers for all gas-containing components such that a failure in a single barrier cannot lead to a fuel gas release into the space. The main differences between the two machinery space concepts are shown in the Figures 2 and 3. The non-hazardous machinery space also shows the GVU room. This may be a separate space outside of the machinery space, or a GVU unit, which is a self-contained unit that is essentially an extension of the double barrier piping system and may be located within the non-hazardous machinery space.

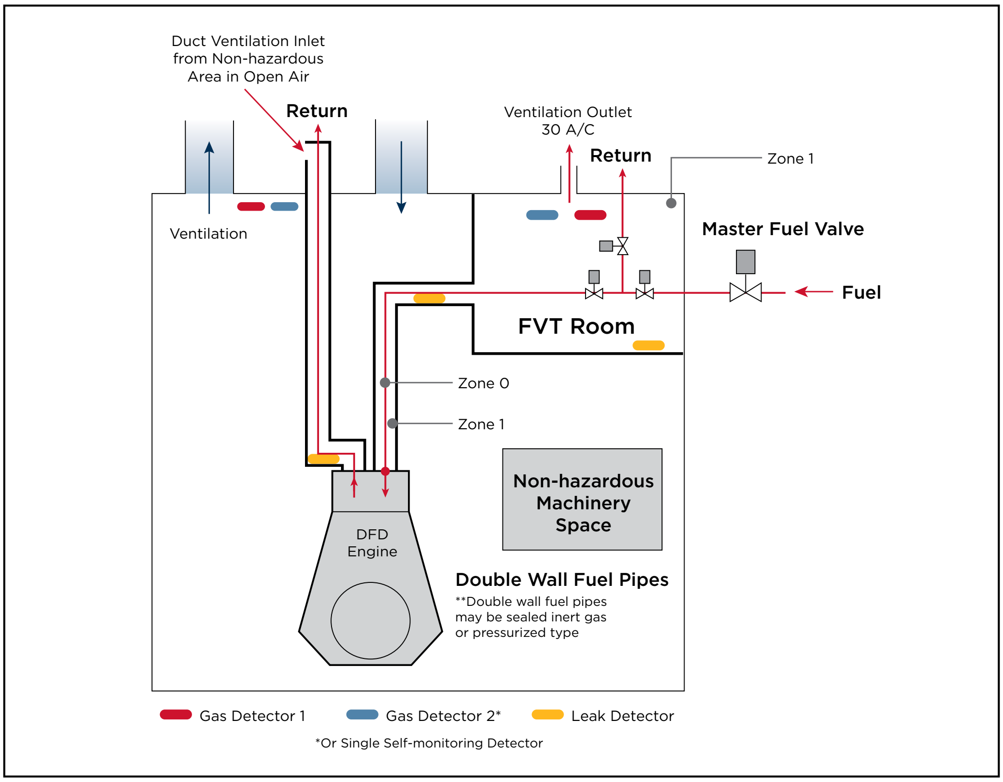


Figure 2: IGF non-hazardous machinery space concept.

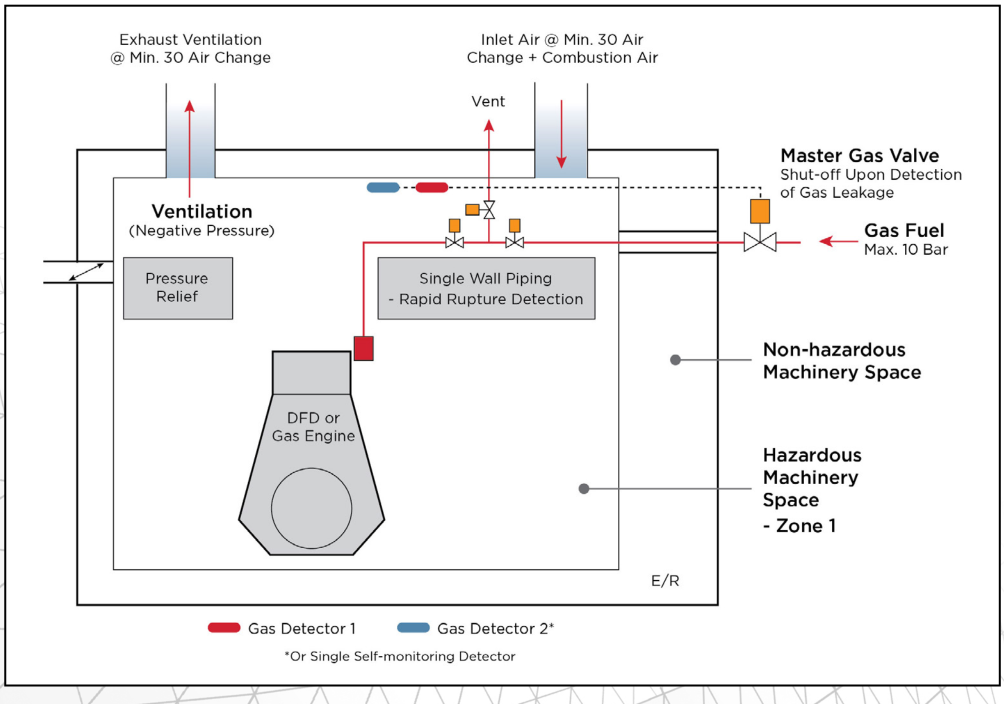


Figure 3: IGF ESD machinery space concept.

Vessels must also find practical locations that meet the prescriptive requirements for the fuel preparation room, vent mast and the nitrogen-generating equipment, as per the ABS *Guide for LNG Fuel Ready Vessels*. The LNG fuel containment system vent mast location can be challenging because of the requirements on hazardous area zones around the vent mast exit and the physical location criteria for the LNG tank pressure relief valve vents. These need to be at least 10 meters (m) from any air intake, air outlet or opening to accommodation, service and control spaces or other non-hazardous areas and any exhaust system outlet. Vent heights shall normally not be less than B/3 or 6 m. The ABS Guidance Notes on Gas Dispersion Studies of Gas Fueled Vessels may be referenced for additional guidance on gas dispersion studies associated with alternative vent termination locations and proposed hazardous areas. Hazardous areas are challenging due to the location of tanks, fuel gas piping systems, FGSS and gas consumers.

KEY DESIGN REQUIREMENTS

Based on the sections above, the following points summarize the main high-level issues to consider in the initial specification discussions for DF LNG vessels:

1. Ensure that non-hazardous machinery space is selected. The ESD machinery space concept introduces additional measures to provide an equivalent level of safety to the conventional non-hazardous machinery space adding vessel complexity and cost.

2. Refer to the ABS ***Guidance Notes on Gas Dispersion Studies of Gas Fueled Vessels*** for additional guidance associated with alternative vent termination locations and proposed hazardous areas.

3. As per most gas-fueled ships in operation, it is recommended to select IMO Type C pressurized fuel tanks because these are relatively inexpensive to manufacture and simple compared to the other fuel containment types, particularly in the smaller sizes required by the current gas-fueled fleet.

4. If a membrane tank is used, other considerations will need to be addressed compared to pressurized tanks due to the major differences in complexity during new construction. Namely, the choice of material for the surrounding hull (ballast, cofferdam), a more complex BOG management system, which could include subcooling, an upscaling of the nitrogen gas generating system and a reinforcement of the membrane and insulation as mid-filing sloshing effect will be bigger than for conventional LNG carriers using the same containment.

5. The tank's natural boil-off rate (BOR) will be provided, and BOG management protocols will be presented, including the IGF Code 15-day holding time criteria.

6. Despite no requirement for FGSS redundancy for DF engines, for practical reasons, duplication of rotating and reciprocating FGSS equipment, such as submerged LNG pumps or high-pressure cryogenic pumps, is recommended for redundancy, reliability and maintenance purposes.

7. Bunkering must be considered at the beginning of a design project for optimum design results. If during the design stage the trading route is known and the potential bunker supplier along the route is identified, measures/contracts can be established so that the parameters of the LNG vessel during bunkering and the supplier/bunker vessel are aligned and procedures of bunkering standardized. If trading routes and suppliers are unknown, then it might be beneficial to increase the equipment limits on the ship so that issues arising from bunkering are handled correctly.

CH_3OH

DF METHANOL VESSEL

Methanol's uptake and application as a marine fuel is only beginning, as it was approved for inclusion in the IMO's Interim Guidelines for Low-Flashpoint Fuels in November 2020. Methanol may be used on board ships as fuel for internal combustion engines or as a fuel source for fuel cell operation.

Methanol is a widely shipped commodity and used in a variety of applications, such as the chemical industry, for many decades. The supply chains exist and are well-positioned to reliably supply methanol as a marine fuel in many ports worldwide. As methanol is a liquid at ambient temperature, the existing liquid fuel infrastructure may also be leveraged to supply methanol with limited conversion. Existing conventional bunker vessels may also be a viable option for maritime bunkering once suitably modified.

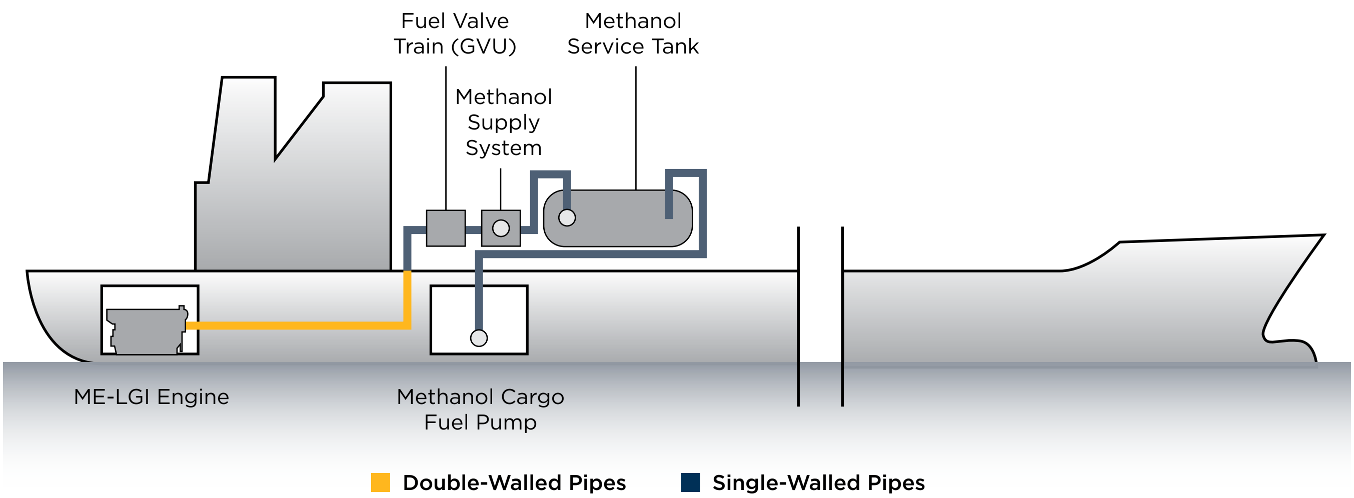


Figure 4: Installations on board new-build methanol ship.

The on board containment of methanol is easier than LNG. As a liquid fuel, only minor modifications are needed to existing systems/infrastructure used for conventional marine fuels. The modifications are mainly due to the high flammability and the low-flashpoint characteristics of methanol.

Major safety considerations include:

- Methanol tank location
- Methanol protection
- Inerting and venting of a methanol tank
- Spill containment
- Vapor and fire detection
- Firefighting

Methanol distribution infrastructure and the availability of engines are catching up to natural gas. Still, the real-world experience of large commercial marine ships demonstrates that methanol is a serious contender for a long-term future marine fuel. Ship operators running methanol fleets would be able to procure methanol with relative ease. Methanol is available at more than 120 ports worldwide and shipped globally. Today, there are more than 90 methanol production facilities all over the world, with an annual supply of nearly 100 million metric tons (Mt) (Methanol Institute, 2023).

Green methanol production projects have been announced across the world. In the short term, green methanol will be produced mainly from biomass; it is therefore expected to be produced first from Asia and South America. In China, there are more than 10 projects that have been announced in the first half of 2024 (at least three of which are expected to begin delivering from 2025 to 2026), with production capacity ranging from 150,000 to 1 million tonne per annum (mtpa). Europe's largest green methanol plant, which has an estimated annual production capacity of 300,000 tonnes, will begin operating in 2028. After 2027, we will see a substantial amount of green methanol supplied from China and other regions.

According to the International Renewable Energy Agency (IRENA), by 2050 e-methanol and biomethanol — green methanol — are expected to make up nearly 80 percent of total production, which could reach 500 mtpa. Whether produced from gray, blue or green feedstocks, the methanol molecule will have the same physical properties, facilitating the transition of marine methanol over time as more low-carbon and net carbon-neutral methanol enters the global supply chain.

FUEL CONTAINMENT

In addition to achieving a lower carbon footprint, the liquid state of methanol makes it easy to store and readily available for bunkering. For onboard storage, low-flashpoint fuels that are liquid at ambient conditions, such as methanol or ethanol, can be stored in conventional fuel tanks with a controlled tank venting system and thus can be simpler to apply compared to liquefied gaseous fuels. Methanol is often proposed for locations below the waterline. This can promote the use of several ballast tanks as potential fuel tanks. However, these tanks need special coatings (zinc, etc.), and due to the low flashpoint, they may require a nitrogen blanket for the tank vapor space. Regardless of the fuel or technology selected, the decision process is very vessel-specific and additional cofferdams or hold spaces, as well as A-60 fire insulation, may also be required.

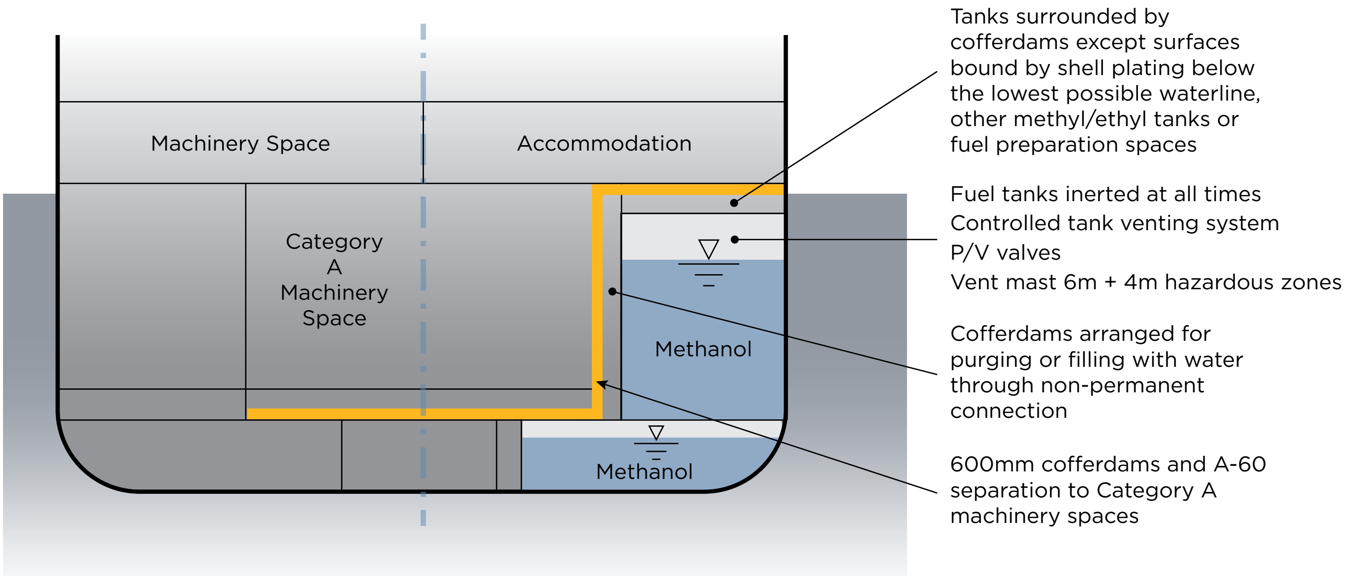


Figure 5: Methanol tank location.

FUEL SUPPLY SYSTEM

Two different FSS are required, depending on the type of methanol-burning engine.

One type of FSS required involves relatively low fuel supply pressure, with all high-pressure pumping is done within the injector. The engines' methanol FSS is significantly simpler compared to LNG without the need for cryogenic storage and handling. The fuel supply to the engine can be accomplished using a low-pressure system, e.g., 10 bar.

The other type of FSS requires a high-pressure (600 bar) fuel pump room as well as the installation of the double-wall fuel piping system with associated safety systems.

For both low- and high-pressure systems, the similarity to LNG is the safety considerations due to the high flammability characteristics of the methanol fuel and its low flashpoint.

ENGINES

All methanol-powered marine engines so far are DF engines, capable of running on both methanol and traditional marine fuels, such as heavy fuel oil (HFO) or marine diesel oil (MDO). This allows the vessel to use methanol when available and switch to conventional fuels when necessary, ensuring operational flexibility.

These engines are designed to optimize combustion for both fuels, using specialized injectors, compression settings and combustion strategies.

Most of the engine designers of methanol-burning engines have adopted the high-pressure diesel combustion process for utilizing methanol.

Fuel injection is accomplished by either a booster fuel injection valve that raises the injection pressure up to 550 to 600 bar, or by a common rail injection system. The first application of this concept was in methanol-burning DF engines on several methanol carriers.

For the DF combustion concept, i.e., the diesel process in oil and low-flashpoint fuel modes, the MCR and transient response performance is equivalent to the conventional oil-fueled engine range and operates with no fuel slip. This prevents the development of any formaldehydes in the exhaust gas. Formaldehyde can cause cancer, and it is classified as a carcinogen by several health organizations, including the Environmental Protection Agency (EPA) and the International Agency for Research on Cancer (IARC).

The DF methanol engines can run on liquid methanol and fuel oils as pilot fuels (low sulfur MDO/HFO or biofuels) depending on the operator preference, fuel availability, air pollution consideration and relative fuel cost. Both two-stroke and four-stroke methanol-fueled engines are available. Cylinders are placed in-line or in a V-shape depending on the total power output of the engine.

BUNKERING

Fuel supply, infrastructure and bunkering of methanol remain as challenges for its widespread adoption. While developing bunkering infrastructure for methanol, lessons can be learned and adapted from the use of LNG as marine fuel. Bunkering facilities, onboard containment systems, FSS and marine engines are the key aspects that need to be assessed for the use of methanol as a marine fuel.

The bunkering station must have adequate ventilation and preferably located on the open deck. For semi-enclosed or closed bunkering stations, effective mechanical ventilation must be provided and may also require a risk assessment.

As a liquid fuel in ambient conditions, bunkering equipment and practices for methanol are much closer to that for conventional fuel oil bunkering. Historical expertise and best practices have been developed through the chemical tanker sector and ships subject to the International Code for the Construction and Equipment of Ships Carrying Dangerous Chemical in Bulk (IBC Code), but also through the offshore sector with the experience gained through handling methanol for drilling operations. For example, the United States Coast Guard (USCG) CG-ENG policy letter 03-12 provides USCG policy for implementation of IMO Resolution A.673(16) for the handling of hazardous and noxious liquid substances in bulk on offshore support vessels (OSVs), with specific requirements for handling methanol. The IMO has adopted Resolution A.1122(30), the Code for the Transport and Handling of Hazardous and Noxious Liquid Substances in Bulk on Offshore Support Vessels (OSV Chemical Code), which now supersedes the IMO Resolution A.673(16).

SAFETY CONSIDERATIONS

FIRE PREVENTION AND DETECTION

The *Interim Guidelines for the Safety of Ships using Methyl/Ethyl Alcohol as fuel (Maritime Safety Committee* (MSC).1/Circ.1621) and the Methanol Institute Safe Handling Guide give provisions for methanol fire detection and firefighting techniques.

Methanol as a liquid does not vaporize rapidly at ambient temperature and pressure as a liquefied gas would. However, methanol vapor in concentrations between 6 to 36 percent of air is flammable when introduced to an ignition source.

Any methanol manifold, ventilation or pressure/vacuum (P/V) relief valve requires an appropriate clear adjacent area to avoid the introduction of ignition sources or sparks.

The autoignition temperature of methanol gas is 450º C, which requires electrical equipment to be assigned a T2 surface temperature class.

Inert gas can protect methanol tank vapor space from explosive behavior. In addition to the risk of explosion, CO_2 in the presence of methanol and moist or salty conditions can create corrosive conditions. Therefore, inert gases containing CO_2 should be avoided, and nitrogen gas is to be used to blanket methanol.

Methanol is known for burning with a low-light and low-temperature flame, and therefore, flame detection if burning pure can be especially difficult. To protect against methanol fires, flame detection equipment such as infrared (IR) cameras, foam extinguishing systems and robust operational procedures must be in place. Methanol flames do not produce smoke or soot, so a smoke detector will not likely be an effective source of fire detection. Heat detector-type fire detection systems may also be unreliable for methanol due to the flame's low temperature.

Flame detectors with IR light detection are ideal for detecting methanol flames. Soot particles in typical fire smoke tend to absorb electromagnetic radiation from CO_2. However, as there is no soot from methanol flames, CO_2 radiation is more significant, and the flame is easily detected in the IR light region. Some flame detectors only alarm when light from both the ultraviolet (UV) and IR regions are detected, but these are not to be used for methanol flame detection.

Vapor detection can also be used simultaneously for leak and fire detection by monitoring oxygen and CO_2 levels. Closed-circuit television (CCTV) can also help with fire detection, and IR cameras used in conjunction with CCTV could be used for methanol flame detection, but these may incur added expenses beyond what is minimally necessary.

Protection against leaks adjacent to methanol tanks or pipes must include gas detection systems near expected leak points, as well as positions near the ceiling and in surrounding low points. Alarms for gas detection should be sensitive enough to alarm well before the concentration levels reach toxic or flammable levels.

Tank overflow and leak protection must be adequate for the holding arrangement in place to prevent flammable conditions in areas with potential ignition sources. In some cases, additional safety measures for cofferdams should be in place to prevent a potentially dangerous buildup of methanol liquid or vapor.

CORROSION

Methanol is corrosive to certain materials, and using methanol as a marine fuel may require the redesigning of some combustion engine parts. Corrosion-inhibiting additives or special coatings could also be an option to reduce methanol corrosion.

The conductivity of methanol increases its corrosiveness in the presence of certain metallic materials such as aluminum and titanium alloys. These materials are commonly used in natural gas and distillate fuel systems but may not be used for pipes or fittings intended for methanol fuel or methanol fuel blends.

Storage tanks holding methanol are to have an appropriate grade of stainless steel or methanol-resistant coating to the tank interior. If coatings are used, it is important to consider that any acidic impurities can damage the coating material, and these damages are to be addressed quickly before accelerated corrosion occurs, including pitting, iron pick-up and further methanol contamination.

Non-metallic materials used in fuel tanks and pipes are to consist of appropriate methanol-compatible materials, such as nylon, neoprene or non-butyl rubber.

TOXICITY

When carried as cargo, the IBC Code classifies methanol as a toxic substance. In addition, most Safety Data Sheets also categorize liquid methanol as a toxic chemical.

The handling of methanol is to be carried out carefully as it contrasts with conventional marine fuels by its toxicity and danger to humans. Crews are to be properly trained and be aware of the additional hazards and characteristics of methanol, including in the case of leaks, spills or exposure. The Interim Guidelines for the Safety of Ships using Methyl/Ethyl Alcohol as Fuel (MSC.1/Circ.1621) provide guidelines for crew safety.

CARBON DIOXIDE FIRE EXTINGUISHING SYSTEM

When comparing CO_2 fire extinguishing system capacity for methanol fires with conventional fuel oil fires, it's important to understand the differences in fire behavior, fuel characteristics and the amount of CO_2 required to suppress each fire type. Both diesel oil and methanol present unique challenges, but the general principles of extinguishing are similar — CO_2 works by displacing oxygen and reducing the temperature to extinguish the fire.

Requirements refer to a free CO_2 gas volume equal to at least 40 percent of the volume of the space protected for conventional fuel oil fires. However, based on the characteristics of a methanol fire, as well as considering the research and theoretical studies conducted in the industry, the minimum extinguishing concentrations for methanol fires compared to conventional fuel fires should be increased by about 25 percent to assure an equivalent effect.

Considering the above, the International Association of Classification Societies (IACS) published the Unified Interpretation (UI) GF21 requiring that where CO_2 fire-extinguishing systems are used as fixed gas fire-extinguishing systems for machinery space or fuel preparation space in methanol-fueled vessels, the quantity of CO_2 carried is to be sufficient to give a minimum volume of free gas equal to 50 percent of the gross volume of the largest space protected, including the machinery space casing.

This UI is to be uniformly implemented by IACS societies on ships contracted for construction on or after 1 January 2026, to which the Administration has required the application of MSC.1/Circ.1621

KEY DESIGN REQUIREMENTS

Based on the sections above, the following points summarize the main high-level issues to consider in the initial specification discussions for DF methanol vessels:

- Inert gas protects the methanol tank vapor space from explosive behavior. Inert gases that contain CO_2 are to be avoided, and nitrogen gas is to be used to blanket methanol. In addition to the risk of explosion, CO_2 in the presence of methanol and moist or salty conditions can create corrosive conditions. Flame detection equipment such as IR cameras, foam extinguishing systems and robust operational procedures are to be in place to protect against methanol fires. Methanol flames do not produce smoke or soot, so a smoke detector will not likely be an effective source of fire detection. Heat detector-type fire detection systems may also be unreliable for methanol due to the flame's low temperature
- The handling of methanol is to be carried out carefully as it contrasts with conventional marine fuels by its toxicity and danger to humans. Crews are to be properly trained and be aware of the additional hazards and characteristics of methanol, including in the case of leaks, spills or exposure. The Interim Guidelines for the Safety of Ships using Methyl/Ethyl Alcohol as Fuel (MSC.1/Circ.1621) provide guidelines for crew safety.
- Methanol is corrosive in the presence of aluminum and titanium alloys, which are commonly used in fuel systems for natural gas and distillate fuels. To solve this problem, it is possible to apply corrosion inhibiting additives or coatings, provided they are not likely to be damaged by acidic impurities. Alternatively, or additionally, non-metallic materials such as nylon, neoprene or non-butyl rubber can be used in fuel tanks and pipes.
- The bunkering station is to be provided with adequate ventilation and is to be preferably located on the open deck. For semi-enclosed or closed bunkering stations, effective mechanical ventilation is to be provided and may also require a risk assessment.
- Methanol is often proposed for locations below the waterline. This can promote the use of a number of ballast tanks as potential fuel tanks. However, these tanks need special coatings (zinc, etc.), and due to the low flashpoint may require a nitrogen blanket for the tank vapor space. Regardless of the fuel or technology selected, the decision process is very vessel-specific. Additional cofferdams, holding spaces or A-60 fire boundaries may also be required.
- For DF methanol engines, combustion is initiated with a pilot injection of conventional fuel oil. Operation indicates slightly improved efficiency over the diesel variant, expected sulfur oxides and particulate matter reductions from the clean fuel, and NO_x reductions of 40 to 50 percent. The NO_x reductions are not large enough to achieve IMO Tier III levels and thus would require exhaust aftertreatment or blending water with the methanol. If blending water with methanol, a separate NO_x compliant aftertreatment system is required to achieve NO_x Tier III compliance when in fuel oil mode.

DF AMMONIA VESSEL

Ammonia as a fuel has additional challenges before being commercially available for the non-gas carrier fleet. Ammonia-fueled engines are under development, and ammonia use is also being explored in fuel cells. Ammonia can be a zero-carbon fuel and provide solutions for the decarbonization of the global fleet. Nevertheless, the cost of producing ammonia-based fuels and making them safe for marine use is being explored. Apart from the cost of adapting infrastructure, ammonia is toxic to humans and aquatic life. Therefore, considerable safety measures must be taken.

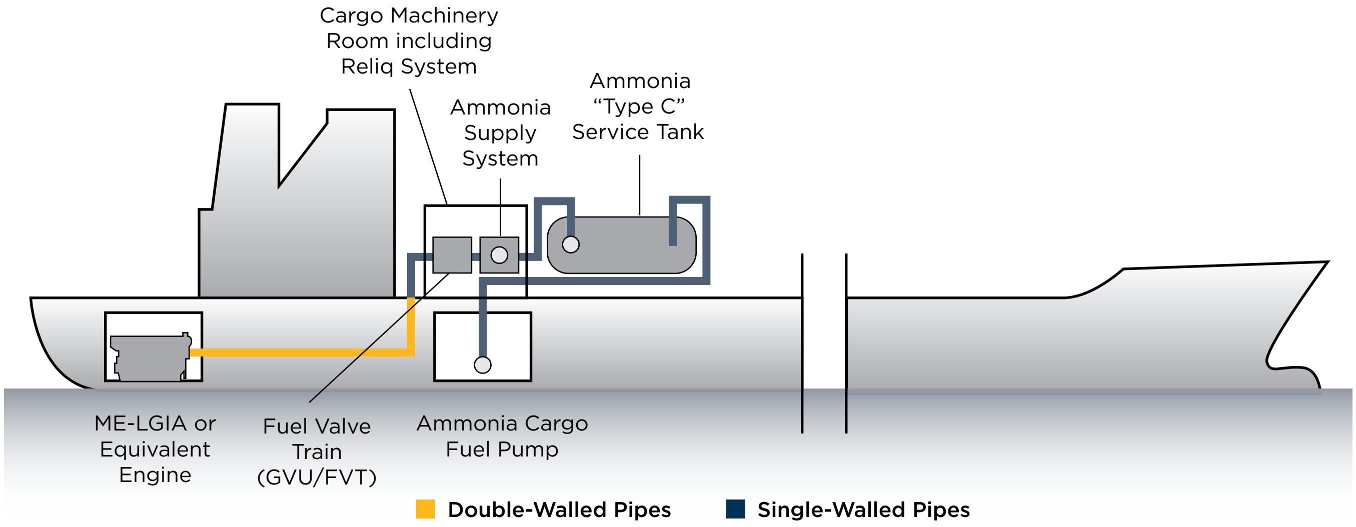


Figure 6: Installations on board new-build ammonia tanker.

When used as fuel in internal combustion engines, ammonia combustion predominantly produces water and nitrogen. Unburnt ammonia must be closely controlled. Guidance on acceptable limits to avoid plume formation or human health hazards can be drawn from other regulatory requirements, where limits of 2 to 10 ppm may be applied. The IMO NO_x limits would also be applicable upon the combustion of ammonia.

Fuel containment, distribution and supply systems can be based on existing technologies and prescriptive requirements. In a liquid state, ammonia is not flammable and cannot ignite. However, it vaporizes rapidly, and the vapor has a narrow flammable range. The main concern is toxicity, and additional measures are needed to control normal and abnormal discharges.

Understanding the requirements of ammonia gas, including low-temperature service, pressurized storage tanks, flammable gases and working with corrosive and toxic materials, is key to addressing the safety hazards of using ammonia as a marine fuel. Some of the considerations when using ammonia as fuel on a vessel are:

- Corrosion
- Design
- Equipment failure
- Cascading failures
- Safety management plan
- Personnel training to reduce human error

Ammonia is currently produced in large quantities as an input for products in the fertilizer and chemical industries. No shipping contracts have been signed but supply agreements have been negotiated between suppliers and energy majors such as Jera (Blue Ammonia from the U.S. to Japan). Existing LNG producers and oil majors are already expanding their blue ammonia plants to meet the forecasted demand. To realize the large-scale production of green ammonia for maritime shipping, its production capacity, along with that of renewable electricity and green hydrogen, will need to grow tremendously. Current projections for the growth in global production appear to indicate there will be enough renewable electricity to produce the volumes of green ammonia needed for the maritime fleet alone by 2040. However, by that time, shipping will also be competing with other industries for renewable electricity and green hydrogen necessary to produce ammonia, as well as with other sectors that also depend on the consumption of ammonia, such as agriculture (EMSA, Sept 2023).

FUEL CONTAINMENT

Ammonia maintains a liquid state at refrigerated (-33° C and 1 bar) or pressurized (20° C and 8.6 bar) conditions. Industrial scale storage uses low temperatures, which requires energy to maintain. This option may have a lower capital cost than pressurization in some cases due to the lower storage design pressures. However, pressurized storage in Type C tanks may be a convenient marine solution even though the IMO *Interim Guidelines for the Safety of Ships Using Ammonia as Fuel* mandate that the temperature of the liquefied ammonia in the fuel tanks at a temperature of no more than -30° C at all times. Besides, the pressure accumulation options introduced in IGF Code applicable to liquified fuel tanks is not listed as a valid option for ammonia fuel tanks in the Interim Guidelines.

As ammonia has low energy content, it will require larger tanks for storage, and their location on board will be a critical design factor. When ammonia is used as a fuel, the changes in vessel arrangement are dependent on the location and type of ammonia tank/containment system. Cargo capacity is also expected to decrease based on the use of ammonia combustion engines or ammonia fuel cell arrangement employed. The additional space for fuel, due to lower energy density, may require larger vessels sizes, decreased cargo space or more frequent bunkering.

Ammonia tanks need to comply with the requirements of the IGC and IGF Codes on minimum distances from the hull's shell, accommodation space, design and safety requirements, etc. However, this is part of the risk assessment route for approval. The IGC Code contains specific material requirements for ammonia fuel containment under Section 17.12, and these are expected to be applied, as applicable, for marine fuel storage tanks.

FUEL SUPPLY SYSTEM

The purpose of the FSS is to deliver fuel at the correct temperature and pressure to the engine. Using gaseous fuels introduces complexity to the fuel supply and consumer systems, creating greater interdependence between the key systems over conventional fuel systems. For fuels using low temperature/pressurized liquefied storage, such as ammonia, the fuel can be pumped or pressure fed directly in liquid form.

The FSS can be one of the more complex and expensive systems required for gas-fueled applications. The FSS needs to increase fuel supply quantities depending on the engine fuel demand. This transient fuel demand can be a challenge, particularly when maintaining fuel supply readiness in times of high demand or zero demand, without causing a shutdown of the FSS. It may also not be part of the engine's original equipment manufacturer (OEM) supply but solely designed to comply with the engine's OEM specifications. Systems for ammonia as a fuel are similar to what is specified for liquefied petroleum gas (LPG), though they are designed for a slightly higher pressure and 2.4-time larger flow. In addition, a system to collect and avoid the release of ammonia vapor must be included.

Liquid fuel systems can be simpler than gas systems. However, this depends on the properties of the fuel being used and the prime mover technology.

ENGINES

Methanol is widely recognized as an effective intermediate solution for reducing GHG emissions, whereas ammonia is considered a long-term solution. Consequently, the development of ammonia engines is not yet at the same level as that of methanol engines.

ABS is witnessing the beginning of ammonia engines for maritime applications, with a few projects selected and approximately 50 ships firm orders (Feb. 2025). More testing is underway, with adjustments on pilot fuel and additional ammonia slip and nitrous oxide (N_2O) mitigation measures.

Burning ammonia in an internal combustion engine uses either the Diesel or Otto Cycle principle. Each combustion cycle comes with its advantages and challenges with respect to engine and FSS design, engine performance and emissions. In general, the low-pressure concept is for engines adopting the Otto Cycle and high-pressure for those using the Diesel Cycle.

Ammonia has a high auto-ignition temperature, a high heat of vaporization and a narrow flammability range. Due to these characteristics, ammonia typically requires a pilot fuel injection. High-pressure injection systems can help minimize ammonia slip; an important consideration given its toxicity.

Slow flame velocity, ignition temperature, narrow flammability range and lower heat of combustion are issues for ammonia ignition. Engine control strategies by engine manufacturers can address these issues. The advent of electronic engine controls and existing DF technologies, including the diesel process, shows promise in addressing these issues.

Ammonia has a high heat of vaporization (1,371 kJ/kg), which results in considerable evaporative cooling of the mixture after injection and reduces the cylinder temperature at the start of combustion, helping to control NO_x formation.

In the Diesel Cycle, the ammonia is injected into the combustion chamber at a high pressure in liquid form. The engine's behavior is the same as when it operates on diesel fuel. Therefore, it is expected that the ammonia is being burned with very limited ammonia slip and the amount of ammonia in the cylinder lubrication oil is negligible. Since most of the ammonia fuel is burned, limited amounts will land on the liner and piston. Therefore, it will likely have a very limited impact on liner wear and on combustion chamber components in the engines. However, the biggest impact is expected to be on the injectors.

In the Otto Cycle, the ammonia is mixed with air prior to combustion resulting in a higher amount of ammonia slip, N_2O and NO_x. Exhaust gases must be treated accordingly with aftertreatment systems to reduce ammonia releases to the atmosphere. Unburnt ammonia will be present in the combustion chamber, so the combustion chamber component will be exposed to ammonia. Therefore, corrosion of the engine component can potentially be an issue, but it is unknown how big the impact will be on the wear and tear of the engine component.

Ammonia combustion and slip emissions mitigation can be achieved by:

- Selective catalytic reduction (SCR)
- Exhaust gas recirculation, however this solution is not currently offered
- Engine design optimization and tuning

The choice of aftertreatment technology can vary depending on the engine type (two- or four-stroke) and combustion cycle (Diesel Otto Cycle).

- Diesel Cycle Engines: Initial results suggest that these engines may achieve Tier III NO_x emission levels through engine tuning alone, potentially eliminating the need for SCR. Ammonia slip is also expected to be low as initial indications from engine makers show potential for meeting the 30 ppm target without additional treatment.
- Otto Cycle Engines: Initial testing indicates higher NO_x and ammonia slip in the exhaust compared to Diesel Cycle engines. This might necessitate a larger SCR catalyst to remove NO_x and additional ammonia injection to achieve Tier III compliance. Moreover, higher N_2O emissions might require an additional N_2O reduction catalyst integrated into the SCR system.

FUEL CELLS

The use of ammonia in fuel cells is still relatively experimental. However, the current pace of development is accelerating, with large stationary plants currently under development. To use ammonia in fuel cells, the hydrogen contained in the molecule must be separated. Although it is possible to achieve this through an external reformer so that the hydrogen can be used in low-temperature fuel cells such as a polymer electrolyte membrane (PEM), using ammonia directly in high-temperature fuel cells such as a solid oxide fuel cell (SOFC) can be a more efficient solution.

There are also other advantages of using ammonia in SOFC, such as high electrical efficiency, the absence of NO_x production and the lack of vibration. Fuel cell development is not as mature as internal combustion engines and typically has a higher cost. These factors are expected to show gradual improvement as research continues. An additional shortcoming of SOFC compared to PEM is the sensitivity of the solid oxide ceramic materials used to heat gradients, which require relatively long and careful start-up and shut-down procedures and often last for hours. Ideally, SOFC plants should run continuously to minimize the risk of permanent damage. This would typically require the use of batteries for energy storage to accommodate fluctuations in the load demand.

BUNKERING

Bunkering is an indispensable operation of supplying fuel to a ship for use by the ship's machinery. Conventionally, any fuel/oil used for this purpose is called bunker fuel or bunker oil. Currently, in the marine industry, ammonia is a bulk commodity frequently loaded/unloaded from gas terminals to ships and ships to gas terminals. The operation is similar to bunkering. The difference is that ammonia is transferred to a dedicated fuel storage tank instead of a cargo tank.

As a new bunker fuel, ammonia will necessitate a complete establishment of provisions and guidelines for a successful start-up. Previous experience from the fertilizer and chemical industry, and the recent development from LPG/LNG bunkering will help inform the process. It is necessary to find gaps between established industry and marine bunkering context and solutions to align operations using technical and operational measures. Ammonia can be stored in liquid form pressurized, semi-refrigerated or fully-refrigerated depending on the needed volume for safe storage, varying from small pressurized 1,000-gallon nurse tanks up to liquefied 30,000 metric ton storage tanks at distribution terminals.

During transfer from one tank to another, either cold inbound or warm inbound is chosen as a result of the transferred volume and re-refrigeration process. The capacity of an onshore full-pressure non-refrigerated tank is usually limited, and the handling can be energy-intensive. Lessons learned have identified high-risk areas such as leakage when handling and toxicity. Measures need to be taken to avoid leakage, handle toxicity and maintain equipment in good working condition through regular inspection.

The use of anhydrous ammonia in fertilizers, SCR reagents and refrigerants has provided enormous knowledge and experience in handling and transporting ammonia. This extensive established chemical/process industry infrastructure can be leveraged and extended to marine terminals and ports.

Due to the similar physical properties, operational experiences on LPG bunkering will provide additional useful guidance in creating ammonia bunkering procedures. Three modes of future ammonia bunkering via truck, tank or ship are envisaged. However, being chemically far from LPG, the safety aspect of ammonia will deserve a separate study that may benefit from the established chemical industry, where safety precautions, material compatibility and machinery are meticulously addressed.

SAFETY CONSIDERATIONS

For ammonia fueled vessels, the specific vessel arrangements will vary depending on the actual fuel pressure and temperature settings of the fuel. The prime mover selected and fuel storage conditions will also affect the vessel design. The links between fuel storage, fuel preparation and fuel consumer are much more interdependent than with conventional fuels. It is critical that equipment and system design decisions consider this interdependence. For ammonia-fueled ships, the main systems that require different or additional concepts in ship designs are the ammonia fuel containment system, associated ammonia bunker station and transfer piping, an FSS, an ammonia release and mitigation system, BOG handling, reliquefication, fuel valve unit/train, nitrogen generating plant, vent piping systems and masts, and for some ammonia tank types, additional equipment for managing tank temperatures and pressure. Water spray, water screen and deluge systems, specific personal protective equipment, independent ventilation for ammonia spaces, emergency extraction ventilation and closed fuel systems may also be required.

VENTING AND DISPERSION

Continuous mechanical ventilation of the spaces where ammonia is used and stored is required. The ABS *Requirements for Ammonia Fueled Vessels* and IMO *Interim Guidelines for the Safety of Ships Using Ammonia as Fuel* are to be used for guidance when conceptualizing the design. ABS Rules provide guidance on the independence of the ventilation system, manning, air changes, stopping of ventilation fans, closing the ventilation openings, air inlet positioning, exhaust duct positioning, etc. Increased or emergency mechanical ventilation systems, that should be activated automatically in the case of ammonia leakage detection, are also required in those spaces.

The ABS *Requirements for Ammonia Fueled Vessels and IMO Interim Guidelines for the Safety of Ships Using Ammonia as Fuel* are also to be used for the limits of the toxic areas around the ventilation inlets/outlets and other openings of the spaces where ammonia is used and vent mast on deck. A gas dispersion analysis should also be carried out in order to determine the extent of the toxic areas to ensure safe distances from the toxic areas to the safe spaces, such as accommodation, service and machinery spaces, control stations, etc.

KEY DESIGN REQUIREMENTS

Based on the sections above, the following points summarize the main high-level issues to be considered in the initial specification discussions for DF methanol vessels.

1. As the links between fuel storage, fuel preparation and fuel consumer are much more interdependent than with conventional fuels, it is critical that equipment and system design decisions consider this interdependence.

2. Refer to the ABS ***Rules for Building and Classing Marine Vessels*** (MVR) 5C-18-6/3.3.3 for initial guidance when conceptualizing the design of mechanical ventilation of the spaces where ammonia is used and stored. Guidance is provided on the independence of the ventilation system, manning, air changes, stopping of ventilation fans, closing the ventilation openings, air inlet positioning, exhaust duct positioning, etc. Special attention must be paid to the location of the vent mast.

3. For ammonia tanks, risk assessment should consider the requirements of the IGC and IGF Codes on the minimum distances from the hull's shell, accommodation space, design and safety requirements, etc. The IGC Code contains specific material requirements for ammonia fuel containment under Section 17.12, and these would be expected to be applied, as applicable, for marine fuel storage tanks.

4. Special attention is required to the engine type selected, due to the pros and cons of each type. For Diesel Cycle, the engine's behavior is the same as when it operates on diesel fuel with very limited ammonia slip and the potential to achieve Tier III NO_x emission levels through engine tuning alone. For Otto Cycle, the ammonia is mixed with air prior for combustion resulting in higher amounts of ammonia slip, N_2O and NO_x. Exhaust gases will have to be treated accordingly with aftertreatment systems to reduce ammonia releases to the atmosphere.

5. When bunkering ammonia, measures need to be taken to avoid leakage, handle toxicity and maintain equipment in good working condition through regular inspection. Bunkering procedures may use operational experiences from LPG bunkering due to similar physical properties. The safety aspect of ammonia will deserve a separate study that may benefit from the established chemical industry, where safety precautions, material compatibility and machinery are meticulously addressed.

REGULATORY CONSIDERATIONS

IGF CODE

Historically, the International Convention for the Safety of Life at Sea (SOLAS) has prohibited the use of low-flashpoint fuel oils less than 60° C, except for use in emergency generators where the limit is 43° C, and subject to several additional requirements detailed under SOLAS II-2 Regulation 4.2.1. In parallel, the IMO adopted the IGF Code, which serves as an international standard for ships operating with gas or low-flashpoint liquids as fuel, other than those ships covered by the IGC Code.

The IGF Code is mandatory by SOLAS II-1 Part G. The adoption of the IGF Code introduced a framework and requirements under SOLAS for burning fuels with a flashpoint less than 60° C.

With the adoption of the IGF Code and 2016 IGC Code, the IMO established the regulatory safety requirements and framework for using natural gas and other low-flashpoint fuels on all ship types. In all cases, the prescriptive and goal-based objectives apply the following three safety principles and general arrangements to mitigate the risks of using low-flashpoint fuels:

- Prevention of leakage, e.g., double barriers, sealing systems, protective locations, cofferdams and air locks
- Prevention of explosive or toxic atmosphere, e.g., ventilation, gas detection, hazardous area classification, master gas fuel valves, fuel block and bleed valves, inert gas barriers and fuel purge systems
- Explosion mitigation, e.g., explosion relief valves, pressure vent systems, design for worst case pressure rise, specialized fire detection and firefighting equipment.

Although the IGF Code has been developed for using fuels with low flashpoint, prescriptive requirements are currently applicable to natural gas only. Other low-flashpoint fuels may also be used as marine fuels, provided they meet the intent of the goals and functional requirements of the IGF Code and provide an equivalent level of safety with natural gas. This approval process is by application of the alternative design criteria under 2.3 of the IGF Code and equivalency shall be demonstrated as specified in SOLAS II-1/55, which refers to the engineering analyses submitted for approval (by the Administration) to be based on the MSC.1/Circ.1212/Rev.1 guidelines.

Alternative fuels have drawn a lot of interest from the marine industry for the potential to become a long-term solution for decarbonization. The IMO has already adopted MSC.1/Circ.1621, the *Interim Guidelines for the Safety of Ships using Methyl/Ethyl Alcohol as Fuel*. The Sub-Committee on Carriage of Cargoes and Containers (CCC) 9 established a work plan, referenced below in Table 2, for the development of several standards for other alternative fuels through the IGF Code. The scope of the remaining work extends to 2026 and includes the development of standards for low-flashpoint oil fuels, hydrogen, ammonia, fuel cells and methyl/ethyl alcohol fuel standards. It may also extend to the development of a mandatory instrument for the use of fuel cells and methyl/ethyl alcohols. The approval of the guidelines for ships using ammonia as fuel is planned for approximately the end of 2024 during the MSC 109 meeting.

Meeting	Objectives	Year
ISWG-AF 1	• Further develop/finalize guidelines for ships using hydrogen as fuel • Further develop/finalize guidelines for ships using ammonia as fuel	9–13 September 2024
CCC 10	• Prepare amendments to the IGF Code on natural gas • Finalize guidelines for ships using hydrogen as fuel • Finalize guidelines for ships using ammonia as fuel • If time permits, further develop guidelines for low-flashpoint oil fuels • If time permits, begin the discussion on the development of mandatory instruments regarding methyl/ethyl alcohols	16–20 September 2024
MSC 109	• Approval of the guidelines for ships using hydrogen as fuel • Approval of the guidelines for ships using ammonia as fuel	2–6 December 2024
CCC 11	• Further develop/finalize guidelines for low-flashpoint oil fuels • If time permits, develop mandatory instruments regarding methyl/ethyl alcohols • If time permits, begin the discussion on the development of mandatory instruments regarding fuel cells	September 2025
MSC 111	• Approval of the guidelines for low-flashpoint oil fuels	May 2026
CCC 12	• Further develop/finalize mandatory instruments regarding methyl/ethyl alcohols • Further consider the development of mandatory instruments regarding fuel cells	September 2026

Table 2: CCC 9 work plan for the development of safety provisions for alternative fuels.

ABS RULES AND REQUIREMENTS

ABS embeds into our Rules the two IMO codes related to the carriage and use of natural gas and other low-flashpoint fuels. The IGC Code is incorporated under Part 5C, Chapter 8 of the ABS MVR for specific vessel types, Vessels Intended to Carry Liquefied Gases in Bulk, and the IGF Code under Part 5C, Chapter 13 for Vessels Using Gases or other Low-Flashpoint Fuels. Part 5C, Chapter 8, and Chapter 13 of the Rules incorporate additional ABS requirements and interpretations and applicable IACS unified requirements and interpretations. The text of the statutory codes is shown in italics to differentiate between the statutory code text and additional ABS or IACS text.

ABS provides requirements for the use of alternative and DFs on board:

- ABS *Rules for Building and Classing Marine Vessels* (MVR)
- ABS *Requirements for Methanol and Ethanol Fueled Vessels* (2024)
- ABS *Requirements for Ammonia Fueled Vessels* (2023)
- ABS *Guide for Gas and Other Low-Flashpoint Fuel Ready Vessels*

In addition, ABS provides guidance on the topic:

- ABS *Advisory on Gas and Other Low-Flashpoint Fuels*
- ABS *Bunkering of Liquefied Natural Gas-Fueled Marine Vessels in North America (Second Edition)*
- ABS *LNG Bunkering: Technical and Operational Advisory*
- ABS *Methanol Bunkering: Technical and Operational Advisory* (2024)
- ABS *Ammonia Bunkering: Technical and Operational Advisory* (2024)
- ABS *Sustainability Whitepaper Ammonia as Marine Fuel* (2020)

EMISSIONS COMPLIANCE

Climate change or global warming is primarily caused by humans burning fossil fuels, increasing GHGs like CO_2 and methane. Greenhouse gases absorb some of the heat that the Earth radiates after it warms from sunlight. Larger amounts of these gases trap more heat in Earth's lower atmosphere, causing global warming.

The IMO estimates that emissions from shipping in 2050 will range from 1,200 Mt CO_2/year in a low-emission scenario to 1,700 Mt CO_2/year in a high-emission scenario and have set a target to reduce this.

The maritime industry is currently undergoing an energy transition, which is being driven by the imperative to mitigate climate change and an ever-changing regulatory environment. An unprecedented transition from conventional fossil fuels to alternative energy sources and the implementation of cutting-edge technologies define the sector's endeavors. A number of initiatives aimed at reducing greenhouse gas (GHG) emissions have been implemented or are in the process of being implemented in accordance with the revised GHG Strategy of IMO.

The IMO updated its initial strategy at the Marine Environment Protection Committee (MEPC) 80th session, which set ambitious goals for future pollution reduction targets compared to 2008 levels. The revised strategy includes the following targets:

- For carbon intensity:
  - 40 percent reduction by 2030
  - Uptake of zero or near zero technologies, fuels/energy sources by at least 5 percent, striving for 10 percent
- GHG emissions:
  - Net zero by or around 2050
- Indicative checkpoints:
  - 20 percent, striving for 30 percent, by 2030
  - 70 percent, striving for 80 percent, by 2040

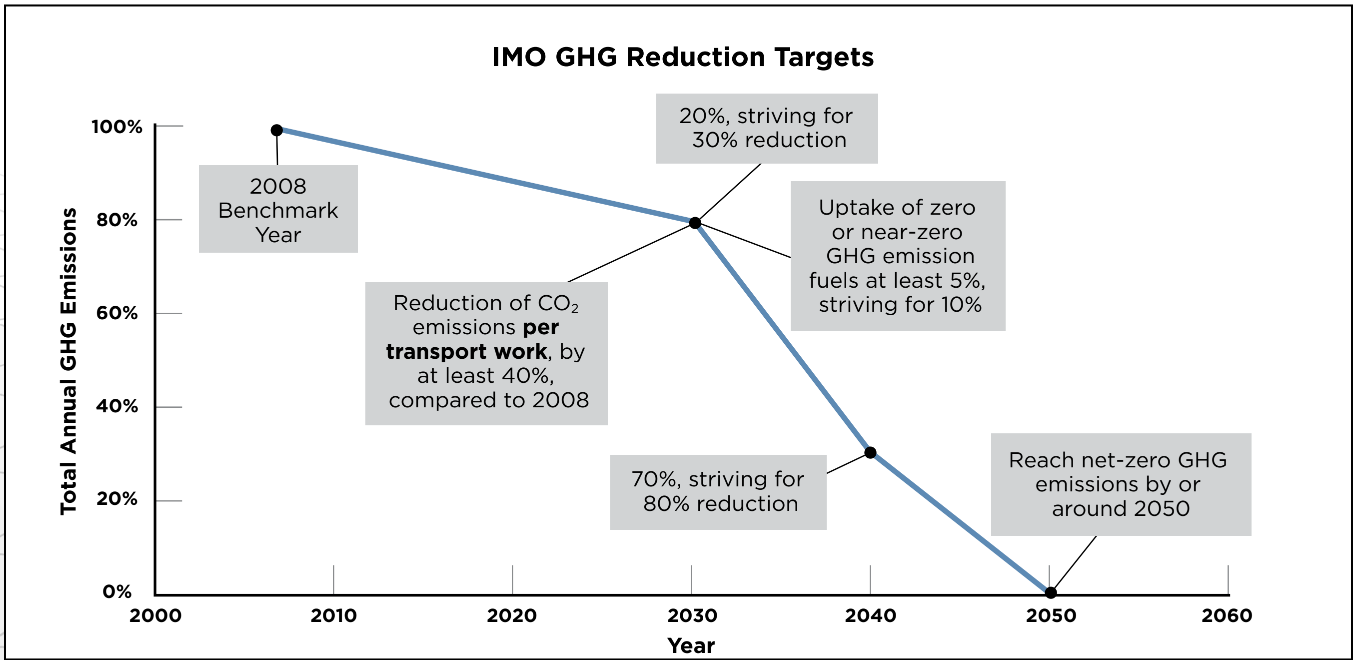


Figure 6: IMO GHG reduction targets.

In addition, market-based measures (MBMs) are included in the strategy to incentivize GHG reduction. Several MBMs have been proposed, and MEPC 81 did not provide clarity on which of the candidate measures may be implemented, but it is ABS' opinion that the IMO may follow the EU with a carbon tax and a WtW measure based on GHG intensity. The GHG Fuel Standard (GFS) is under development and expected to be implemented no earlier than 2027.

In addition to the potential MBMs considered by the IMO, the EU has created the Fit for 55 legislative package, aiming to reduce EU GHG emissions by 55 percent by 2030. This package includes the addition of the EU Emissions Trading Scheme (EU ETS) and FuelEU Maritime regulation, with EU ETS implemented in 2024 and FuelEU Maritime beginning at the start of 2025.

These measures apply to voyages of vessels arriving and departing the EU and sailing from EU port to EU port, with a voyage defined as cargo operation to cargo operation.

The EU ETS is an emissions trading scheme, in which emitters will have to buy allowances to cover their CO_2 emissions. These allowances are bought and sold, and speculation may lead to price volatility. As more details of the regulation have come to light with its adoption, it has become apparent that the shipowner submitting the allowances to the EU may be reimbursed by the charterer. As such, the cost of EU ETS may now affect charter rates, as vessels emitting more CO_2 may cost the charter more when transporting their cargo, which may provide benefits for DF vessels. It is worth noting that from 2026 onward, the CO_2e from N_2O will be included in the cost of the EU ETS, which may affect LNG and ammonia-fueled vessels.

FuelEU Maritime imposes a yearly GHG limit with annual reduction targets, which will become more ambitious leading up to 2050 to reflect developments in low-carbon fuel technology and availability. Ships will need to calculate GHG emissions per unit of energy used on board based on their reported fuel consumption and the emissions factors of their respective fuels. FuelEU Maritime adopts a WtW approach to assessing a fuel's emissions factor, which covers the entire life cycle.

The calculated GHG emission intensity greatly depends on the fuel type mix used on board the vessel. This is then compared to the index value. Ships that do not meet the required yearly index will be subject to penalties, whereas meeting the yearly target will lead to credits being allocated.

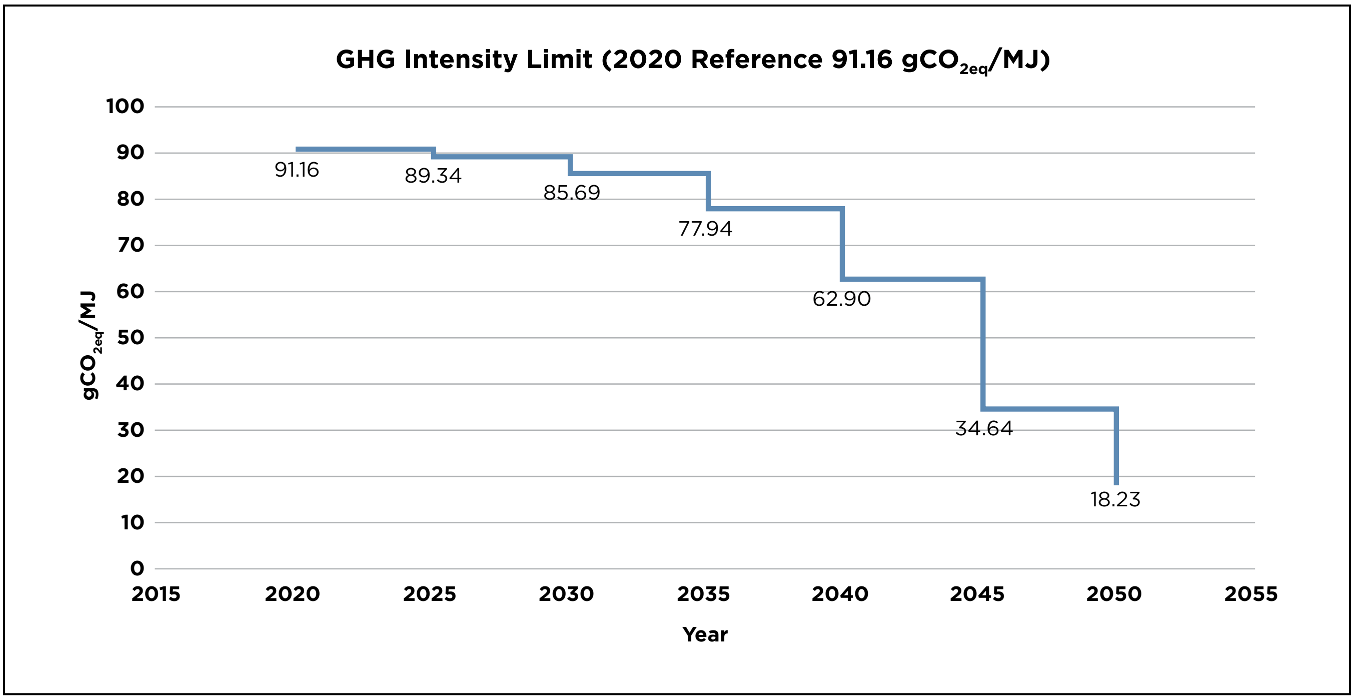


Figure 7: GHG intensity limit.

Year	2020	2025	2030	2035	2040	2045	2050
Reduction	-	-2%	-6%	-14.5%	-31%	-62%	-80%
GHG intensity [gCO_2e/MJ]	91.16	89.34	85.69	77.94	62.90	34.64	18.23

Table 3: GHG intensity reductions.

FuelEU Maritime allows for some flexibility. Rolling over or borrowing excess compliance from one year to another, or pooling compliance between multiple vessels is possible. If a ship has a deficit of compliance units, some may be obtained in advance, though not for over 2 percent of the target, or over two consecutive reporting periods.

COST OF COMPLIANCE

DF EFFECTS ON EU ETS

As EU ETS is based on GHG emissions generated on board the vessel, two paths are available to reduce exposure to EU ETS:

- Reduce fuel consumption
- Reduce the carbon factor of the fuel

Reducing fuel consumption will provide easy but small gains, while larger gains will be difficult to achieve. Changing to alternative fuels will reduce the carbon factor and the number of EU Allowances (EUAs) required. The reduction will depend on the carbon factor and LCV of the fuel to be used, for example:

- LNG-fueled vessel: approx. 25 percent reduction (depending on methane slip)
- Methanol-fueled vessel: approx. 15 percent reduction
- Ammonia-fueled vessel: approx. 80 percent reduction (depending on pilot fuel and N_2O slip)

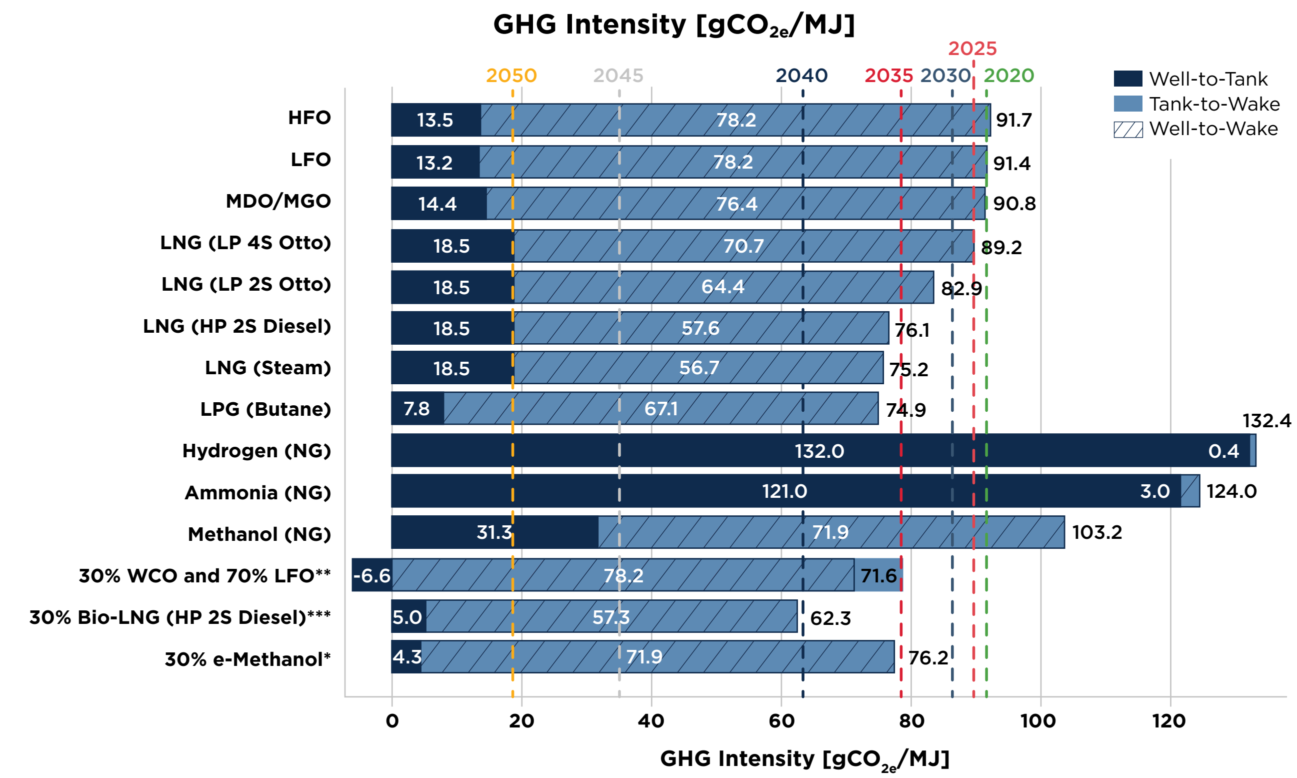
As these reductions may be passed on to the charter, it may be that better charter rates can be negotiated for DF vessels. Conversely, ABS expects charter rates for conventional vessels to start decreasing in the upcoming years.

DF EFFECTS ON FUELEU MARITIME

As FuelEU Maritime considers WtW emissions, the type of fuel (gray, blue or green) is of major importance. These fuel types are defined as follows:

- **Gray Fuel:** Conventional fuel produced from refining hydrocarbons. The vast majority of fuels used in shipping are gray fuels.
- **Blue Fuel:** Similar to gray fuels, but with carbon capture used during the refining process to reduce the amount of CO_2 generated during fuel production (WtT emissions). This does not affect the emissions during use on board the vessel (TtW emissions).
- **Green Fuel:** Either biofuels or synthetic fuels (created from electrolysis of water using green electricity, e-fuels), which have very low emissions during production.

When considering the effect of alternative fuels on FuelEU Maritime, it is useful to refer to the graph below:



* e-Methanol (89% GHG reduction)
** Hydrotreated oil from waste cooking oil (80% GHG reduction)
*** Biomethane for transport (Open digestate, no off-gas combustion) (69% GHG reduction)

Figure 8: GHG intensity limit and most common fuels.

Using the graph, we can now discuss each DF option:

- DF LNG: For DF LNG, the most popular engine type (due to lower methane slip), is the two-stroke Diesel Cycle type. This is what we will concentrate on here.
- Due to the low WtT emissions and TtW emissions that are approximately 25 percent lower than conventional fuels, a WtW GHG intensity of 76.1 grams of carbon dioxide equivalent per megajoule IgCO$_2$e/MJ) is obtained. This will provide compliance (compliance surplus) with FuelEU Maritime until 2040. Associated with this compliance surplus is the possibility to offset compliance deficits for other vessels by pooling. For compliance beyond 2040, the addition of biogas (30 percent bio-LNG in the graph) will provide further compliance surplus until 2045, and a larger compliance surplus prior to 2040.
- DF methanol: For DF methanol, using gray methanol (102.9 gCO$_2$e/MJ) will create issues with compliance, generating a compliance deficit from 2025. For compliance, green (bio or e-methanol) or blue methanol must be used, possibly as a blend, and the percentage adjusted as and when needed. Looking at the graph above, 30 percent of e-methanol will provide compliance and a surplus to 2040.
- DF ammonia: For DF ammonia, as ammonia does not generate any emissions when combusted on the vessel (TtW) except for the emissions from pilot fuel use, almost all the WtW emissions from a DF ammonia vessel are generated from the production of the fuel. The type of ammonia therefore has the largest effect on FuelEU Maritime regulations.

Using gray ammonia (121 gCO$_2$e/MJ) will lead to higher compliance costs than gray methanol. Green ammonia (approximately 8 gCO$_2$e/MJ) will provide a very large compliance surplus up to 2050, which may offset GHG emissions of many vessels and offset the increased cost of expensive green ammonia.

DF EFFECTS ON IMO GHG MBMS

As stated on page 23, as the IMO hasn't concluded on which MBMs will be adopted, it is the opinion of ABS that the IMO may follow the EU with a carbon tax and a WtW measure based on GHG intensity and the GFS.

This could be approximate to a global application of EU ETS and FuelEU Maritime. By using this simplification, the conclusions drawn above can be used for the IMO GHG MBMs, but all the costs and effects would be amplified, namely:

- Carbon tax:
  - LNG-fueled vessel: approximately 25 percent reduction (depending on methane slip)
  - Methanol-fueled vessel: approximately 15 percent reduction
  - Ammonia-fueled vessel: approximately 80 percent reduction (depending on pilot fuel and N_2O slip)
- GFS, assuming similar targets to FuelEU Maritime:
  - DF LNG: Due to the low WtT emissions and TtW emissions that are approximately 25 percent lower than conventional fuels, a WtW GHG intensity of approximately 76 gCO_2e/MJ is obtained. This may provide compliance until 2040.
  - For compliance beyond 2040, the addition of biogas may provide further compliance surplus.
  - DF methanol: Using gray methanol (approximately 103 gCO_2e/MJ) will create issues with compliance from the adoption of GFS. For compliance, green (bio or e-methanol) or blue methanol must be used, possibly as a blend and the percentage adjusted as and when needed.
  - DF ammonia: For DF ammonia, the type of ammonia has the largest effect on compliance. Using gray ammonia (120 gCO_2e/MJ) will create bigger issues with compliance than gray methanol. Green ammonia (approximately 8 gCO_2e/MJ) may provide compliance to 2050.

ECONOMIC ANALYSIS OF CANDIDATE DF VESSEL OPTIONS

When considering the costs associated with selecting a DF vessel, comparing these costs to the expected cost of an equivalent conventional vessel is beneficial. Four categories must be considered:

- Fuel costs
- Regulatory compliance costs
- Investment cost (and payback)
- Chartering

Each will be considered in the following table.

Regarding the fuel costs, comparing the estimated evolution of very low sulfur fuel oil (VLSFO), methanol and ammonia in dollars per metric ton leads to the following table. Data for gray fuels is not shown as the expected FuelEU Maritime (and GFS) penalties will render these fuels uncompetitive:

Fuel Type	2025	2030	2035	2040	2045	2050
VLSFO	$650/MT	$550/MT	$500/MT	$480/MT	–	–
LNG						
LNG	$800/MT	$550/MT	$540/MT	$540/MT	$530/MT	$530/MT
Biogas	$1,100/MT	$1,060/MT	$990/MT	$930/MT	$860/MT	$800/MT
e-LNG	$2,700/MT	$2,200/MT	$2,000/MT	$1,800/MT	$1,500/MT	$1,200/MT
Methanol						
Biomethanol	$710/MT	$600/MT	$550/MT	$520/MT	$480/MT	$460/MT
Synthetic (e-fuel)	$1,400/MT	$1,100/MT	$990/MT	$850/MT	$700/MT	$570/MT
Ammonia						
Blue	$670/MT	$500/MT	$490/MT	$480/MT	$470/MT	$460/MT
Green	$950/MT	$650/MT	$580/MT	$510/MT	$430/MT	$350/MT

Table 4: Estimated evolution of fuel costs.

The costs are obtained from various sources in the industry and combined with internal ABS data. It is worth noting that approximately 1.7 times more methanol is needed and two times more ammonia compared to a conventional vessel. Pilot fuel (5 to 15 percent) should also be considered. Subsidies may be made available to reduce the cost of these lower and zero-carbon fuels, but more information isn't currently available.

For the regulatory compliance costs, pages 26, 27 and 28 provide the information required to estimate the cost effect. As these costs will directly depend on the fuel type and consumption, a simpler way to present the cost effects is to compare to the base VLSFO case.

Then a "+" can be used to show a higher cost of compliance than VLSFO and a "–" to show a lower cost. Multiples of each are used to facilitate the comparison.

Fuel Type	EU ETS	FuelEU	IMO Carbon Tax	IMO GFS
VLSFO	0	0	0	0
LNG				
LNG	- -	- -	- -	- -
Biogas	- -	- - -	- -	- - -
e-LNG	- -	- - -	- -	- - -
Methanol				
Gray	-	+	-	+
Green	-	-	-	-
Ammonia				
Gray	- - -	+	- - -	++
Blue	- - -	- -	- - -	- -
Green	- - -	- - -	- - -	- - -

Table 5: Regulatory compliance cost comparison.

For FuelEU Maritime (and maybe GFS), pooling will help monetize the compliance surplus.

Regarding the investment costs and the payback of the investment in a DF vessel, we can look at each option in turn:

- DF LNG: Due to the properties of the LNG, this is potentially the most expensive of the DF vessels for the fuel containment and FSS (usually Type C tanks and high-pressure pumps). The main machinery cost might be similar to ammonia machinery.
- DF methanol: As methanol is liquid at ambient temperature, it is the cheapest and easiest system considered here (special coatings and cofferdams around the fuel tanks).
- DF ammonia: As the temperature needed to liquify ammonia is higher than the temperature for LNG, containment and fuel supply costs may be lower than the equivalent LNG vessel.

Regarding the payback of the investment, various techno-economic analysis undertaken by ABS show that selling an existing vessel and replacing it with a DF vessel will not repay the investment. But if the comparison is the replacement of a vessel with a conventional or a DF vessel, in most cases, there is a breakeven point between the conventional and DF of 10 to 18 years if the vessel sails sufficiently in the EU for the regulatory advantages of the DF vessel to be monetized. The adoption of the IMO GHG MBMs would potentially reduce this due to the global application of the MBMs. This also considers the potential chartering advantages.

When considering the chartering effects, with the shipowner being able to recoup the cost of the EUAs from the charterer, it is apparent that charter rates for conventional vessels visiting the EU will drop over the next few years. This is not expected to happen for DF vessels due to their reduced compliance cost.

CONCLUSION

Three main DF solutions are considered by international shipping: DF LNG, DF methanol and DF ammonia. The selection of the most suitable technology requires the consideration of multiple factors, which were elaborated in detail in the main body of this advisory.

An overall view of the characteristics of the three alternative fuels is shown below compared to MGO:

Fuel	Boiling Point (° C)	Infrastructure	TtW CO_2 emissions	WtW CO_2 emissions**	Technology Readiness Level	Impact on Newbuilding Ship Cost
Ammonia	-33	• Existing LPG network can be used • > 700 LPG carrier	None	Close to Zero	6	Medium
Methanol	65	• Infrastructure in place • Available in many ports	Approx 15% lower than MGO	Close to zero (even negative)	8-9	~1.9
LNG (Methane)	-163	• Infrastructure under develop • Costly to transport*	Approx 25% lower than MGO (depending on slip)	Difficult to reach zero	9	High

* Possibility to use small LNG carriers as bunker vessels. The situation is improving.
** Fuel produced from either sustainable biomass and/or renewable electricity

Table 6: Overall characteristics of alternative fuel.

The table below summarizes the points requiring further attention when considering the building of a DF vessel:

DF LNG	DF Methanol	DF Ammonia
Non-hazardous machinery space is selected to reduce vessel complexity and cost.	To protect methanol tank vapor space from explosive behavior, nitrogen gas is to be used to blanket methanol.	It is critical that equipment and system design decisions consider the interdependence between the fuel storage, fuel preparation and fuel consumer.
Refer to the ABS *Guidance Notes on Gas Dispersion Studies of Gas Fueled Vessels*.	Flame detection equipment such as IR cameras, foam extinguishing systems and robust operational procedures are to be in place to protect against methanol fires.	Refer to ABS MVR 5C-18-6/3.3.3 for initial guidance when conceptualizing the design of mechanical ventilation of the spaces where ammonia is used and stored.
As per most gas-fueled ships in operation, it is recommended to select IMO Type C pressurized fuel tanks.	The handling of methanol is to be carried out carefully as it contrasts with conventional marine fuels by its high toxicity and danger to humans.	For ammonia tanks, risk assessment should consider the requirements of the IGC and IGF Codes.
If a membrane tank is used, other considerations will need to be addressed (such as choice of material for the surrounding hull, a more complex BOG management system and upscaling the nitrogen gas generating system).	Methanol is corrosive in the presence of aluminum and titanium alloys, which are commonly used in fuel systems for natural gas and distillate fuels.	Special attention is required to the engine type selected due to the pros and cons of each type.
Natural BOR to be provided for the tank and BOG management protocols to be presented, (IGF Code 15-day criteria). For practical reasons, consider duplication of rotating and reciprocating FGSS equipment (submerged LNG pumps or high-pressure cryogenic pumps).	The bunkering station is to be provided with adequate ventilation and is to be preferably located on the open deck. Methanol is often proposed for locations below the waterline. This can promote the use of several ballast tanks as potential fuel tanks with additional cofferdams or hold spaces also required.	When bunkering ammonia, measures need to be taken to avoid leakage, handle toxicity and maintain equipment in good working condition through regular inspection.
Bunkering is to be considered at the beginning of a design project for optimum design results.	If blending water with methanol to achieve NO_x Tier III, a separate NO_x compliant aftertreatment system is required to achieve NO_x Tier III compliance when in fuel oil mode.	– – –

Table 7: Points requiring further attention when considering the building of a DF vessel.

As the main goal for the adoption of a DF vessel is emission compliance, it is important to consider the costs of this compliance, both in terms of potential savings from compliance and additional costs from operation and investment for each of the three options presented in this report.

	DF LNG	DF Methanol	DF Ammonia
EU ETS/ IMO Carbon Tax	-25% cost compared to MGO	-15% cost compared to MGO	Approximately -80% cost compared to MGO
FuelEU Maritime/ IMO GFS	**Gray LNG:** Compliance to 2040 **Green LNG:** Compliance to 2045+	**Gray Methanol:** Non-compliant **Green Methanol:** Compliance to 2050	**Gray Ammonia:** Non-compliant **Green Ammonia:** Compliance to 2050
Fuel Cost*	**LNG**	**Bio-Methanol**	**Blue Ammonia**
2025	$800/MT	$710/MT	$670/MT
2035	$540/MT	$550/MT	$490/MT
2045	$530/MT	$480/MT	$470/MT
Fuel Cost*	**Biogas**	**Synthetic Methanol**	**Green Ammonia**
2025	$1,100/MT	$1,400/MT	$950/MT
2035	$990/MT	$990/MT	$580/MT
2045	$860/MT	$700/MT	$430/MT
	DF LNG	**DF Methanol**	**DF Ammonia**
Investment Cost	Highest	Medium	High

* Cost per Mt. Due to LCV, 1.7 to 1.9 times more methanol is needed for the same energy, 2 to 2.2 times more ammonia is needed for the same energy.

Table 8: Overall cost comparison.

LIST OF ACRONYMS AND ABBREVIATIONS

BOG	Boil-off gas
BOR	Boil-off-rate
CCTV	Closed-circuit television
CO_2	Carbon dioxide
DF	Dual fuel
EPA	Environmental Protection Agency
ESD	Emergency shutdown
EU	European Union
EU ETS	European Union Emission Trading Scheme
EUA	European Union Allowances
FGSS	Fuel gas supply system
FSS	Fuel supply system
GFS	Greenhouse gas fuel standard
GHG	Greenhouse gas
GVU	Gas valve unit
HFO	Heavy fuel oil
IACS	International Association of Classification Societies
IARC	International Agency for Research on Cancer
IBC	International Code for the Construction and Equipment of Ships Carrying Dangerous Chemical in Bulk
IGF Code	International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels
IMO	International Maritime organization
IR	Infrared
IRENA	International Renewable Energy Agency
LCV	Lower calorific value
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
m	Meters
MARPOL	International Convention for the Prevention of Pollution from Ships
MBMs	Market-based measures
MCR	Maximum continuous rating
MDO	Marine diesel oil
MGO	Marine gas oil
Mt	Million metric tons
mtpa	Million tonnes per annum
N_2O	Nitrous oxide
NO_x	Nitrogen oxide
NTC	NO_x Technical Code
OEM	Original equipment manufacturer
OSV	Offshore support vessel
PEM	Polymer electrolyte membrane
ppm	Parts per million
SCR	Selective catalytic reduction
SOFC	Solid oxide fuel cell
TtW	Tank-to-Wake
UI	Unified Interpretation
USCG	United States Coast Guard
VLSFO	Very low sulfur fuel oil
WtT	Well-to-Tank
WtW	Well-to-Wake

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