Review of LNG and Methanol Marine Fuel Options

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10 March 2022

Methanol vs. LNG key takeaways:

- **CO_2e footprint of Blue Methanol is 5–10% lower than LNG, combining well-to-gate production footprint and hull-to-wake consumption footprint.**
- **Methanol fuel costs are less volatile than LNG, and today, methanol is roughly half the cost.**
- **A methanol-fueled engine adds ≈10% to the cost of a new vessel, LNG engine adds 22% more.**
- **Methanol is easier to handle and store than LNG, with half the bunkering time.**
- **Methanol bunkering infrastructure is easier and cheaper than LNG bunkering infrastructure.**
- **Path to a carbon-neutral methanol fuel is being developed, but no path exists for LNG.**

In November 2020, the International Maritime Organization announced that it aims to reduce absolute shipping emissions by at least 50% from 2008 levels by 2050, and attempt to eliminate them completely thereafter.

Energy Efficiency Design Index (EEDI) was made mandatory by the IMO with the adoption of amendments to MARPOL Annex VI.[1]While the improvements outlined there will affect overall energy efficiency and emission levels of the maritime industry, the IMO is also driving the switch to alternative maritime fuels. The applicability of alternative fuels in the maritime sector is highly dependent on the fleet type, ship use, ship technical performance, investment costs, environmental impact, and the geographical bunkering location that indirectly determines the availability of alternative fuels.

Shipping's decarbonization goals need immediate action if Sustainable Development Goals are to be met by 2050, but choosing a winner from among the alternative fuels that are currently available remains difficult. Each fuel—whether Liquefied Natural Gas (LNG), methanol, electric batteries, hydrogen, or ammonia—comes with its own set of advantages and limitations, with no one-size-fits-all approach. LNG and Methanol are the two near-term alternative fuels under consideration by the shipping industry to meet the IMO greenhouse gas emissions targets.

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[1] "Amendments to MARPOL Annex VI on Regulations for the Prevention of Air Pollution from Ships," MEPC 62/24/Add.1 Annex 19

CO_2e REDUCTION

The adoption of low-carbon and net carbon-neutral fuels for long-range (LR) and medium-range (MR) vessels is more challenging than for smaller vessels travelling shorter routes. Using fuels with lower energy content than petroleum, such as LNG and methanol, will require some substantial vessel redesigns, not least because their fuel tanks would need to be expanded to store enough energy for longer deep-sea travel.

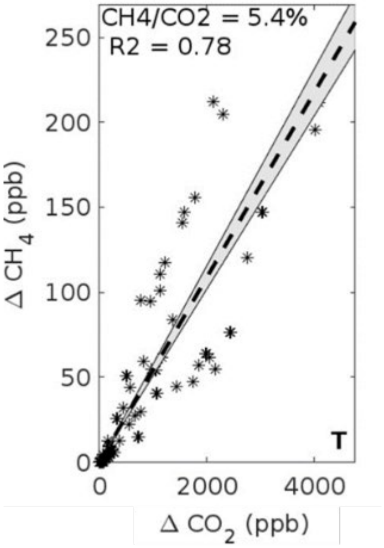

Figure 1. Measured methane slip from LNG ship.

Between LNG and methanol, methanol is better for the environment as it has a lower CO_2e footprint[2] and, even if some methanol slips through the combustion process to the exhaust, it doesn't have the same global warming consequence as methane slip. Maersk, a leader in clean marine transport, has said that they "will not use LNG as a marine fuel, because of the methane slip problems with it."[3]

Figure 1 depicts the measurements of an LNG ship's emissions. [4] Note that the methane emissions are only about 5% of CO_2 emissions as measured in parts per billion. However, because the 20-year Global Warming Potential (GWP) of methane is 87 times as great as CO_2, the emissions of methane are much more problematic than the CO_2 emissions. Ultimately, the effective reduction in CO_2 emissions realized by this LNG vessel is offset by the increased CO_2e emissions from the methane slip. By contrast, methanol that might slip to the exhaust in a dual-fuel engine is not a GHG, and has a half-life of less than a few hours in the air.

For ship owners reporting, understanding the full life cycle CO_2e emissions of using LNG and methanol will be required. The Well-to-Gate, or Product Life Cycle Assessment, is an important component in evaluating fuel sourcing.

In addition to evaluating the emissions created by combusting the fuels, a Product Life Cycle Assessment (PLCA) for alternative marine fuels includes both the emissions created during the extraction of the natural gas and its conversion to a liquid fuel, either mechanically to LNG or chemically to methanol. While there is one basic process for producing LNG, there are several processes for converting natural gas to methanol fuel. Here we introduce the difference between i) traditional grey methanol, ii)

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[2] CO_2e - carbon dioxide equivalent - created by the Intergovernmental Panel on Climate Change (IPCC) in order to compare the effects of gases with different global warming potential

[3] F Toud, "Is methanol the best fuel to meet shipping's green goals?" Ship Technology Journal, September 2, 2021

[4] T Grönholm et al, "Evaluation of Methane Emissions Originating from LNG Ships Based on the Measurements at a Remote Marine Station" Environ. Sci. Technol. 2021,55,13677−13686

advanced grey methanol, iii) blue methanol, and iv) green methanol. While the final methanol produced is chemically identical, the conversion processes offer significantly different emission profiles.

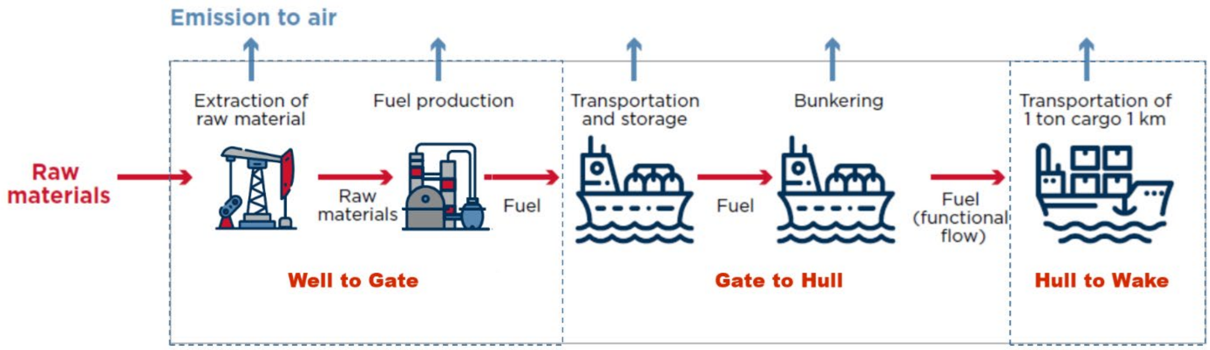

Figure 2 - . IMO MEPC 75/7/15. Reduction of GHG Emissions from Ships, Fourth IMO GHG Study 2020 – Final report. Dated 29 July 2020. While the details of accounting are not yet published, they will require ship owners to include the Product Life Cycle of the fuel, above as Well to Gate, to which must be added emissions from transport of fuel, bunkering and emission for ship usage.

- ***Traditional Grey Methanol***, the majority of all methanol commercially available in the world today, utilizes a Steam Methane Reformer (SMR) that burns significant quantities of natural gas in a fired heater to raise the temperature of catalyst-filled tubes, which convert feedstock natural gas into a syngas[5] that allows for further processing into methanol.
- ***Advanced Grey Methanol*** uses a newer, advanced process where the natural gas conversion to syngas occurs in a sealed vessel, an Autothermal Reformer (ATR), where only the natural gas feedstock is heated, greatly reducing the amount of fuel consumed and the corresponding emissions.
- ***Blue Methanol*** is a more advanced process that uses an ATR, but only a portion of the produced syngas is converted to hydrogen and pure carbon dioxide (CO_2), and the hydrogen (rather than natural gas) is combusted for the required heat for the ATR, thereby generating no carbon-based emissions; the pure CO_2 produced from the syngas is either permanently sequestered underground or used to manufacture additional products, not emitted into the atmosphere. The end result is a near zero-carbon methanol production process.
- ***Green Methanol*** is produced from captured CO_2 and hydrogen electrolyzed from water with all required electrical power coming from renewable sources. While technically feasible, the cost of the Green Methanol process is considerably higher than Grey Methanol or Blue Methanol production processes at this time.[6] Green Methanol will need 10+ MWh of renewable power, wind or solar, for each metric ton of product (which requires access to large quantities of land), together with a significant amount of fresh water at a location that is close to a waterway allowing green methanol to be easily transported. These challenges are quite significant and commercially challenging, therefore, it is not considered in this paper as a scalable near-term marine fuel.

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[5] Syngas is a mixture of hydrogen and carbon monoxide at a ratio of approximately 2 to 1

[6] Electrolyzer manufacturer ThyssenKrupp estimates the production cost of Green Methanol at ≈$800/MT when assuming renewable electricity costs of $0.04/kWh. Each MT of Green Methanol requires 10+ MWH of renewable electricity: Every $0.01/kWh of power costs = $100+/MT of production cost of Green Methanol.

Product Life Cycle Assessments presented below follow the ISO 14040 series standards that address quantitative assessment methods for the assessment of the environmental aspects of a product or service in its entire life cycle stages. The GHG emissions are estimated using the IPCC Fifth Assessment Report global warming potentials for methane and nitrous oxide across two time scales: 100 years (gCH_4 = 36 g CO_2e and gN_2O = 298 g CO_2e and CO_2 -1) and 20 years (gCH_4 = 87g CO_2e, g N_2O = 268 gCO_2e and CO_2 =1)[7] [8] Considering the lifespans of LR and MR vessels are in the 25 year range and the IMO goal to reach net zero by 2050, the 20-year GWP values are the most relevant.

		Production	Gathering & Boosting	Processing	Storage Pipeline & Compression	Conversion	TOTAL
		t Co2e/t fuel	t Co2e/t fuel	t Co2e/t fuel	t Co2e/t fuel	t Co2e/t fuel	t Co2e/t fuel
LNG	100 year GWP	0.140	0.110	0.170	0.18	0.280	0.880
	20 year GWP	0.280	0.170	0.230	0.270	0.280	1.230
Grey Traditional MeOH	100 year GWP	0.070	0.055	0.085	0.090	0.830	1.130
	20 year GWP	0.140	0.085	0.115	0.135	0.830	1.305
Grey Advanced MeOH	100 year GWP	0.070	0.055	0.085	0.090	0.240	0.540
	20 year GWP	0.140	0.085	0.115	0.135	0.240	0.715
Blue MeOH	100 year GWP	0.070	0.055	0.085	0.090	0.050	0.350
	20 year GWP	0.140	0.085	0.115	0.135	0.050	0.525
MGO	**100 year GWP**	**18.889**	**2.196**	**23.282**	**0.879**	**20.793**	**66.040**
	20 year GWP	**51.648**	**2.196**	**23.282**	**0.879**	**20.793**	**98.798**

Figure 3. This table breaks down the Product Life Cycle Assessment, Green House Gas emissions from the cradle (the well head) to the product at the manufacturer's gate for LNG, and the three variations of methanol production. LNG values are from a recent study completed of the Cheniere LNG plant on the US Gulf Coast and are one of few studies using regionally sourced emission values rather than national averages.[9] Methanol conversion values are from engineered mass balances performed by Haldor Topsøe or approved US EPA permits. The lower methanol values prior to conversion reflect that a ton of produced methanol contains only a half-ton of natural gas with the balance being oxygen added in the conversion process.

Three engine manufacturers have come to dominate the market for the giant low-speed two-stroke diesel engines used in the largest LR and MR vessels, bulk carriers, and tankers: MAN SE of Germany, Mitsubishi Shipbuilding, part of Mitsubishi Heavy Industries of Japan;[10] and Wärtsilä of Finland.[11] All offer new and conversion to LNG or methanol dual-fuel options.

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[7] The IPCC (2018) Special Report on Global Warming of 1.5°C suggests that limiting warming to 1.5°C requires anthropogenic methane emissions to begin to decline immediately and to be at least 35% below 2010 levels by 2050. Given that methane has strong warming effects, using the 20-year GWP better aligns with the 2050 goals.

[8] The IPCC Sixth Assessment Report released in 2021 includes moderately lower GHG assessments for methane (gCH_4 = 30g CO_2e for 100 GWP and gCH_4 =83g CO_2e for 20-year GWP), implying 100-year GWP levels for pre-conversion CO_2e emissions, which are dominated by methane leakage, would be 15-20% lower if calculated using the IPCC's latest assessments.

[9] S Roman-White, J Littlefield, K Fleury, D Allen, P Balcombe, K Konschnik, J Ewing, G Ross, and F George." LNG Supply Chains: A Supplier-Specific Life-Cycle Assessment for Improved Emission Accounting" ACS Sustainable Chem. Eng. 2021, 9, 10857−10867

[10] MHI is a licensee of Wärtsilä

[11] The Swiss company, Wärtsilä Switzerland Ltd., responsible for the low-speed, two-stroke engine within Wärtsilä, was merged with China State Shipbuilding Corporation (CSSC) in early 2015 and renamed Winterthur Gas & Diesel Ltd. (WinGD). In 2016, Wärtsilä Corporation transferred its remaining shares of WinGD to CSSC making WinGD 100% owned by CSSC.

Hull-to-wake emissions represent the values associated with burning the fuels in a given engine and the load it is operating under. When combusted all carbon-based fuels combine one carbon atom plus two oxygen atoms to yield one carbon dioxide molecule and heat. Each fuel has a specific carbon content which provides an emission coefficient expresses as kg CO_2/kg fuel. Traditional Marine Gas Oils (MGOs) emit approximately 3.200 kg CO_2/kg fuel while LNG emits 2.750 kg CO_2/kg fuel and methanol emits 1.375 kg CO_2/kg fuel if completely combusted. However, since the objective of the combustion is to produce useful work—in this case turning a propeller shaft—the efficiency of the engine plays a large role. LNG and methanol engines have similar thermal efficiencies. Each dual-fuel engine utilizes MGO as a pilot fuel to assist in the combustion, LNG requires 10% MGO and methanol 1.5% MGO. Ultimately, the hull-to-wake GHG emissions for a methanol engine (69.1 g/MJ) are slightly better than an LNG engine (75 g/MJ).[12]

Single screw, slow speed, two- stroke diesel engine propulsion options for large ships are well established. For a given ship there is no unique solution, rather there is a cluster of solutions whose acceptability is dependent upon the hull form and final choice of prime mover. Assumed throughout our analysis is a 12,500 TEU ship that requires a 67.3 MWh power source to deliver (after shaft line losses) 65.9MWh at 90 RPM on a 9,700mm six blade propeller driven by a tail shaft diameter of 1,042mm experiencing 7,140 N.m of torque. Both two -stroke dual-fuel engines (LNG and methanol) have a thermal efficiency of approximately 48%. This requires 504,720 MJ/h of energy in the fuel.

Figure 4. Reference vessel used in assumption throughout document

Blue Methanol provides a comparable/lower GHG emission profile than LNG in the Well-to-Gate production process as well as a lower GHG emission profile in the Hull to Wake consumption process, indicating that Blue Methanol is a superior fuel to reduce GHG emissions for the shipping business.

		Grams of CO_2e per MJ		
		Well to Gate	Hull to Wake	Combined
LNG	100 year GWP	18	75	93
	20 Year GWP	25.1	75	100.1
Traditional (SMR) Grey Methanol	100 year GWP	56.5	69.1	125.6
	20 Year GWP	65.3	69.1	134.4
Advanced (ATR) Grey Methanol	100 year GWP	27	69.1	96.1
	20 Year GWP	35.8	69.1	104.9
Blue (ATR) Methanol	100 year GWP	17.5	69.1	86.6
	20 Year GWP	26.3	69.1	95.4
MGO	100 year GWP	66.0	74.7	140.7
	20 Year GWP	98.8	74.7	173.5

Figure 5. Carbon footprints of options less the variability of transport to the bunkering facility and the actual bunkering.

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[12] "Green Maritime Methanol WP2 Initiation and Benchmark analysis", TNO 2019 R11732 Traffic & Transport Anna van Buerenplein, The Netherlands

FUEL STORAGE AND COSTS

Unlike LNG, methanol is well suited for storage in conventional fuel tanks which can be easier to accommodate in ship designs than other low-flashpoint fuels, and under MSC.1/Circ.1621 5.2.1 can also be bound by a vessel's shell plating when stored below the lowest possible waterline. This ability to re-purpose existing fuel storage infrastructure lowers the cost of retrofitting vessels to use lower-polluting fuels. Retrofitting a vessel's tanks from conventional fuel oil, ballast, or slop to hold liquid methanol fuel is substantially easier and less costly than installing LNG pressurized tanks.

The below figure illustrates i) the actual energy density of various fuels and ii) the effective density of using those fuels when considering the extra space required for proper storage/bunkering of the fuels, some of which - like LNG - require elaborate refrigerated and pressurized storage infrastructure. The result being that the effective storage densities (ship space required per unit of energy consumed) for methanol and LNG are similar.

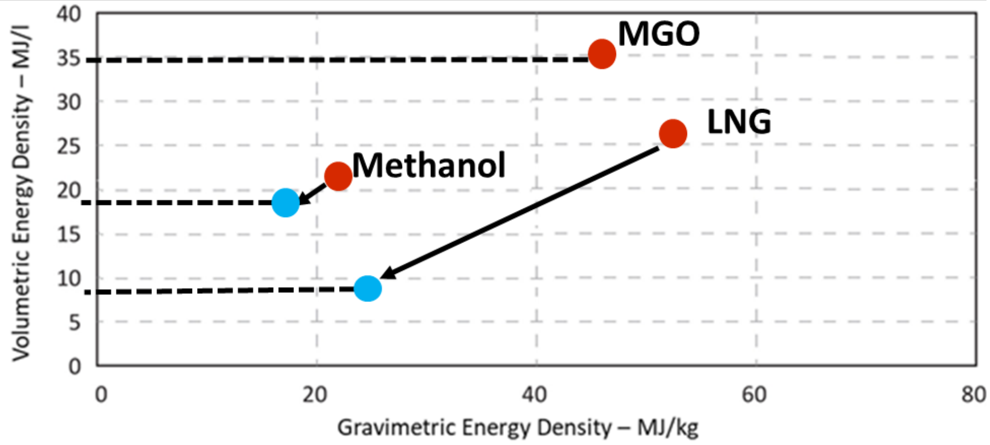

Figure 6. Effective energy densities. The red dots above illustrate the energy density of the fuels only. As shown, LNG fuel has both greater volumetric and gravimetric density than methanol. However, when storage tanks and necessary systems are included, represented by the blue dots, the picture changes radically for LNG because of the specialized refrigerated/cryogenic or pressurized storage that is required to bunker and utilized LNG aboard a ship. Including these specialized infrastructure requirements, the effective gravimetric density of utilizing LNG declines from ≈50 MJ/kg (fuel only) to ≈25 MJ.kg and the effective volumetric density of utilizing LNG declines from ≈26 MJ/l to ≈9 MJ/l. The additional weight and volume required to bunker and use methanol is far more modest. Methanol requires less ship space than LNG for the ship to traverse the same distance. .

Brake Specific Fuel Consumption of a marine diesel engine (BSFC) often shortened to SFC, is a marine engineering term used to describe the fuel efficiency of an engine design. It measures the amount of fuel needed to provide useful power available at the shaft output. The energy contained in the fuel depends on the mass (kg) of the fuel, not on the volume, because the volume depends on temperature.

The below table compares values for low-pressure and high-pressure LNG internal combustion engines (ICE) with that of a methanol fueled engine using 2019 data.[13] Note that testing indicates high-pressure LNG engines have less methane slip.

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[13] 1 megawatt hour (MWh) = 1,341 horsepower hours (hp h) = 3,600 MJ

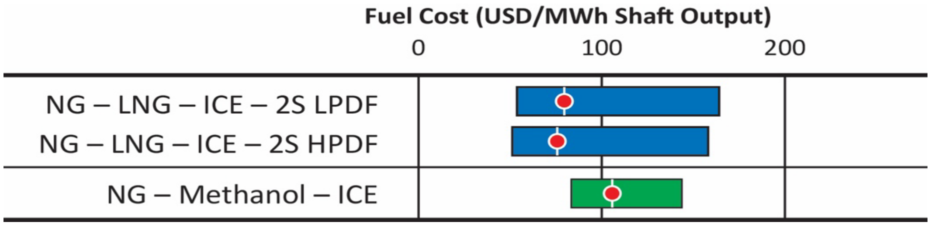

Figure 7. Energy cost for the fuel/technology pathways, taking into account the energy content and system efficiency in LR and MR vessels [USD (2019)/MWh shaft output] [14]

LNG Costs Update: The Red Dots in the chart are based on LNG costs of about ≈$9/MMBTU, yielding a fuel cost of $80-$85/MWH of Shaft Output. The range of costs was based on LNG costs of about $7/MMBTU - $15/MMBTU. At today's LNG price of $30/MMBTU, the fuel costs would be about $280/MWH of Shaft Output.

Methanol Costs Update: The Red Dot in the chart is based on methanol costs of about ≈$300/MT, yielding a fuel cost of $104/MWH of Shaft Output. The range of costs was based on methanol costs of about $250/MT–$400/MT. At today's methanol price of $425/MT, the fuel costs would be about $150/MWH of Shaft Output.

Although not included in the above chart a MGO price update is: At today's global average price of $987/MT, the fuel costs would be about $355/MWH of Shaft Output. Assumptions: 40.2 MMBTU per MT of GMO, 50% engine efficiency as per DVN paper that provided the efficiency estimates for the LNG and Methanol engines.

The investment cost for a methanol-powered vessel are less expensive than for an LNG-powered vessel because the methanol-powered vessel does not require expensive high-pressure fuel tanks, vapor re-liquefaction equipment, and advanced fuel delivery system that the LNG-powered vessel requires.

The choice of fuels should also include an understanding of the availability and bunkering time for each fuel. The LNG bunkering process includes cooldown of equipment, hose connecting and disconnecting, and pumping, taking approximately 30 hours for complete bunkering. Methanol bunkering is comparable to MGO bunkering, averaging less than 14 hours. Building out methanol bunkering infrastructure would also be less onerous and costly than building out LNG bunkering infrastructure.

LNG CHARACTERISTICS AND CONSIDERATIONS

Liquefied natural gas (LNG) is essentially methane (CH_4) that has been chilled sufficiently to reach a liquid state. Methane and methanol (CH_4O) are the hydrocarbon fuels with the lowest carbon content and therefore the highest potential to reduce carbon emissions. LNG is 95+% methane with a net calorific value of 48.6 MJ/kg. Methane is also a potent greenhouse gas,[15] and methane slip from the exhaust and fugitive emission from the vessel, and during bunkering must be kept under control to ensure reductions in GHG emissions.

If LNG were spilled or leaked into water, it would create a vaporization event. When in contact with water, the spilled LNG will accelerate the vaporization process and increase the concentration of vapor in the immediate area. According to the 2004 Sandia report, this is of special concern to ship and pilot-boat crews, emergency response personnel, or others who are exposed in a marine environment. An

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[14] SEA\LNG Ltd "Alternative marine fuels study", DNV GL AS Maritime Environment Advisory, 2019-07-05

[15] Methane has more than 87 times the warming power of carbon dioxide over the first 20 years after it reaches the atmosphere per the Environmental Defense Fund.

ignition source close to the origin of the spill is likely to cause ignition and result in rapid high-heat burn-off of natural gas vapors, rather than an explosion.[16]

LNG COMBUSTION CONSIDERATIONS

LNG is a clean-burning fuel in most respects. Anderson et al [17] performed particle number size distribution and exhaust gas measurements onboard an LNG dual-fuel ship. They found that emissions of particles, NO_X, and CO_2 were clearly lower when using LNG instead of marine fuel oils. Alanen et al, [18] also observed lower particle emissions from an LNG engine, compared to marine diesel oil (MDO) or marine gas oil (MGO). Moreover, Peng et al [19] observed 93%, 97%, and 92% reduction of emissions in particles, black carbon, and NO_X, respectively, when changing from diesel fuel to LNG as a fuel. However, at the same time, the formaldehyde, carbon monoxide, and CH_4 outflow increased several-fold.

The emission of unburned methane emissions in marine engines (also called methane slip) depends on engine load; it is largest at lower loads. Methane slip emissions can impact climate change since methane has 87 times higher global warming potential than CO_2 over a time span of 20 years. As pointed out by Ushakov et al., methane slip had been previously ignored as a pollutant and GHG contributor, but has recently received more attention. A recently published study in the Environmental Science Journal of the American Chemical Society found in a multi-year study of LNG ships passing through a Baltic Sea passage measured concentration peaks $\Delta CH_4/\Delta CO_2$ ranged from 1% to 9%. [20]

The methane slip is caused by the trade-off of the emissions of NO_X and CH_4. A low pressure dual-fuel engine can be optimized to run with a minimal thermal loading, resulting in low NO_X emissions. As NO_x emissions are highly regulated but methane emissions have remained unregulated up to now, it is to be expected that shipping companies would run their LNG engines to minimize NO_X emissions at the expense of creating higher CH_4 emissions. Stenersen and Thonstad [21] reported that of LNG vessels in

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[16] "Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water". Sandia National Laboratories. December 2004.

[17] Anderson, M.; Salo, K.; Fridell, E. Particle- and Gaseous Emissions from an LNG Powered Ship. Environ. Sci. Technol. 2015, 49, 12568– 12575, DOI: 10.1021/acs.est.5b02678

[18] Alanen, J.; Isotalo, M.; Kuittinen, N.; Simonen, P.; Martikainen, S.; Kuuluvainen, H.; Honkanen, M.; Lehtoranta, K.; Nyyssönen, S.; Vesala, H.; Timonen, H.; Aurela, M.; Keskinen, J.; Rönkkö, T. Physical Characteristics of Particle Emissions from a Medium Speed Ship Engine Fueled with Natural Gas and Low-Sulfur Liquid Fuels. Environ. Sci. Technol. 2020, 54, 5376– 5384, DOI: 10.1021/acs.est.9b06460

[19] Peng, W.; Yang, J.; Corbin, J.; Trivanovic, U.; Lobo, P.; Kirchen, P.; Rogak, S.; Gagne, S.; Miller, J. W.; Cocker, D. Comprehensive analysis of the air quality impacts of switching a marine vessel from diesel fuel to natural gas. Environ. Pollut. 2020, 266, 115404, DOI: 10.1016/j.envpol.2020.115404

[20] T Grönholm, T Mäkelä, J Hatakka, J Jalkanen, J Kuula, T Laurila, L Laakso, and J Kukkonen. “Evaluation of Methane Emissions Originating from LNG Ships Based on the Measurements at a Remote Marine Station”, Environ Sci Technol. 2021 Oct 19; 55(20): 13677–13686.

[21] Stenersen D.; Thonstad O. GHG and NO_X emissions from gas fuelled engines; Report no OC2017 F-108; SINTEF Ocean AS: Norway, 2017.

operation, 88% use low pressure dual-fuel engines[22]. As measured, none of the vessels equipped with low pressure dual-fuel engines complied with the IMO Tier II or Tier III limits for methane emissions.[23] [24]

While the methane emissions from high-pressure dual-fuel engines were found to fulfill the goal of reducing the climatic impacts, the methane emissions originating from low pressure dual-fuel engines were found to be substantially high, with a potential for *increased* climatic impacts compared with using MGO.

Low pressure dual-fuel two stroke LNG LR and MR vessels have a thermal efficiency[25] in the 48% range and methane slip of 0.32 kg CH_4/MWh at 25% load and 0.131 kg CH_4/MWh at 100% load while high pressure dual-fuel two stroke LNG ships exhibit a much lower methane slip of only 0.002 kg CH_4/MWh. Smaller and intercostal ships that operate mostly with four stroke engines have lower efficiency and higher methane slip, however they are not considered here.[26]

Methane slip varies as a function of engine load, with higher slip at lower loads. In the wake of the global port bottlenecks and higher fuel costs, shippers have responded by sailing as slower speeds, operating at low engine loads. As a result, current methane slips could be higher than estimated.

Taking only the global warming potential into account, experts suggest the ratio of the emissions $\Delta CH_4/\Delta CO_2$ originating from LNG powered ships should not exceed 1.4%,[27] but no emission directives or standards are currently in place to directly regulate the methane slip for marine LNG engines.[28] However, studies by Det Norske Veritas (DNV)[29] urge that they be prepared, to mitigate the climatic impacts related to the methane slip and fugitive emissions in LNG-powered shipping.

LNG VESSEL CONSIDERATIONS

LNG has taken an early foothold as an alternative marine fuel. Despite this positive sentiment, the high investment cost for LNG storage systems is commonly cited as one of the major challenges in switching to LNG.

LNG's specific energy of 48.6 MJ/kg is higher than marine oil fuels. The boiling point of LNG is approximately -162°C at 1 bar absolute pressure. The design of LNG storage tanks has to adhere to the

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[22] As of 2019 only 90 of the more than 750 LNG-fueled ships in service or on order use HPDF engines.

[23] IMO Annex VI Tier 2 limits range from 14.4 to 7.7 g/kWh, while Tier 3 limits range from 3.4 to 1.96 g/kWh.

[24] T Grönholm, T Mäkelä, J Hatakka, J Jalkanen, J Kuula, T Laurila, L Laakso, and J Kukkonen. "Evaluation of Methane Emissions Originating from LNG Ships Based on the Measurements at a Remote Marine Station", Environ Sci Technol. 2021 Oct 19; 55(20): 13677–13686.

[25] Thermal efficiency is the ratio of the net work output to the heat input.

[26] Olmer, N., Comer, B., Roy, B., Mao, X., & Rutherford, D. (2017). Greenhouse gas emissions from global shipping, 2013-2015. Retrieved from the International Council on Clean Transportation website: https://theicct.org/sites/default/

[27] T Grönholm, T Mäkelä, J Hatakka, J Jalkanen, J Kuula, T Laurila, L Laakso, and J Kukkonen. "Evaluation of Methane Emissions Originating from LNG Ships Based on the Measurements at a Remote Marine Station", Environ Sci Technol. 2021 Oct 19; 55(20): 13677–13686.

[28] Ushakov, S.; Stenersen, D.; Einang, P. M. Methane slip from gas fueled ships: a comprehensive summary based on measurement data. Journal of Marine Science and Technology 2019, 24, 1308– 1325, DOI: 10.1007/s00773-018-00622-z

[29] DNV operates as a quality assurance and risk management company. The Company offers supply chain, data management, technical assurance, software, and advisory services worldwide.

various codes. The type, size and tank locations are important considerations. LNG itself has a density of 450kg/m^3. However, when additional tankage sizes and shapes along with associated equipment are considered, LNG requires approximately 3-4 times the storage space required for MGO.[30]

As heat leaks into the tank, LNG evaporates (i.e. boils off) and slowly increases the tank pressure due to the boil-off gas. The classification society requirement for a minimum holding time of 15 days regulates the minimum insulation requirements for an LNG storage tank. A rectangular or prismatic tank is optimal with respect to space utilization, but it cannot easily withstand internal pressure without adding stiffeners, etc., which add considerable weight and manufacturing effort. Therefore, most LNG tanks are cylindrical/spherical, taking up more space than a rectangular tank would. The challenge to engineers is a set of problems referred to as packing density. The upper bounds of an ordered packing densities of basic 3D objects is cube (1.0) > cylinder and spherocylinder (0.9069) > sphere (0.7405). Since ideal LNG tanks fall in the latter two shapes there will be wasted space when fitting them in rectilinear spaces.

For decades, the standard storage system for transporting various liquid hydrocarbons at low temperatures has been the IGC Code Type-C austenitic steel pressure vessels[31]. Vacuum-insulated LNG storage tanks are normally fitted with 250−300 mm annular space, despite the lower thermal conductivity. An additional constraint comes from the need to install the interconnecting pipes in the annular space. In installations where fast LNG bunkering time is a necessity, the large bunkering pipes may result in an even bigger annular space.

Of the two possibilities, above or below deck, the above-deck LNG storage location is less complex and less expensive. The below-deck LNG storage location requires zoned separation from other spaces, explosion-proof appliances, dedicated ventilation systems, and, in general, more controls. LNG cannot be placed wing tanks[32] or double bottom tanks[33] and thus the volume requirements are many times that of storing MGO. Above deck locations, well away from the vessel's roll and pitch centers, invite greater sloshing and possibly greater structural stress requiring additional supports.

Heat related boil-off gas increases the pressure in the storage tanks, the tanks are designed to handle higher pressures and are fitted with pressure relief valves to allow venting of gas to the atmosphere if the pressures become excessive. For very large tanks, the evaporation rate may be as low as 0.1% of stored LNG per day; for smaller tanks it may be as high as 0.25% per day. Venting boil-off gas into the atmosphere is undesirable from an economic, environmental, and safety perspective and is therefore only allowed in emergency situations and is not permitted as a method for routine pressure control. Venting of the gas is undesirable from an economic, environmental, and safety perspective. The more volatile components of LNG (methane and nitrogen)[34] boil off first, changing the composition and quality of LNG over time. This is known as ageing.

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[30] The Naval Architect: July/Aug 2019,Journal of the Royal Institution of Naval Architects, London

[31] International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code), adopted by resolution MSC.5 (48), has been mandatory under SOLAS chapter VII since 1 July 1986.

[32] Wing tanks are on the sides of the vessel within the bottom wing of each cargo hold

[33] Double bottom tank is fitted between the forward collision bulkhead and the after peak bulkhead. It's top or `inner bottom' forms the deck of the cargo holds and continues out to the ship's side.

[34] LNG specification are 85-97mole % Methane, 4 mole % Butane, 0.2 mole % Pentane and 1,24 mole % Nitrogen

Some methods to manage the boil-off gas are:

> Re-Liquefaction of the gas to LNG. This can be by a direct system, where the gas is compressed and condensed before being returned to the tank. An indirect system condenses or cools the gas with an external refrigerant, without being compressed.
>
> Burning off the excess gas in a thermal oxidizer. On an LNG-fueled vessel, this is primarily done by feeding the excess gas to other engines. If the boil-off gas exceeds the rate at which it can be used, the gas can be fed to a gas combustion unit, which burns the gas in a controlled matter. No useful energy can be recovered from burning the gas in this method.

The location of tanks is important from a safety perspective, with their position being restricted by IMO guidelines. The tanks have to be well insulated, and a surrounding safe area is required in case of accidental spillage.

METHANOL CHARACTERISTICS AND CONSIDERATIONS

Methanol is predominately used as a chemical building block for hundreds of everyday products and is fast emerging as an attractive option for shipping companies looking to reduce their carbon footprint and to meet other sector-wide emissions targets. As methanol is the most transported chemical, many fleets are already familiar with its handling. Methanol has a net calorific value of 19.9 MJ/kg. Methanol is a colorless liquid at ambient temperature and pressure with a characteristic pungent odor. Methanol has the highest hydrogen-to-carbon ratio of any liquid fuel and the most oxygen, a relationship that potentially lowers the CO_2 emissions from combustion when compared to conventional fuel oils. When used as the primary fuel, methanol can reduce CO_2 emissions by around 18% compared to MGO. However, methanol use has the potential to approach carbon-neutral when manufactured in a green production process that constructs methanol using recycled CO_2 and Hydrogen obtained from water hydrolysis powered by renewable electricity.

Methanol fuel is a liquid at ambient conditions, making it simpler to handle and closer in operation to conventional bunker vessels. Methanol is supported by the International Maritime Organization in its recent adoption of safe handling guidelines under the IGC Code for low flashpoint fuels[35]. In addition to methanol being traded and transported in chemical carriers for many years, there is also the experience of the offshore support vessel and platform supply vessel fleets handling methanol for the offshore industry, which can therefore also be reference points for the wider adoption of methanol as a bunker fuel. Methanol is a widely traded commodity with an existing global distribution network that could be easily leveraged to support marine fuel bunkering.

If spilled or leaked into the environment, Methanol has significantly less environmental impact than conventional hydrocarbon fuels. It dissolves readily in water, and only very high concentrations in the environment create lethal conditions or effect on the local marine life. Methanol in the ocean is common, produced naturally by phytoplankton, and is readily consumed by bacteria microbes, thus entering and supporting the food chain.[36]

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[35] The International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels is to provide an international standard for ships, other than vessels covered by the IGC Code, operating with gas or low-flashpoint liquids as fuel.

[36] Panos Koutsourakis "Fueling a low carbon future with methanol as a marine fuel" World Oil, Gulf Publishing Company 7/28/2021

METHANOL COMBUSTION CONSIDERATIONS

Methanol is a sulfur free, toxic, corrosive, and liquid fuel in the ambient state. It requires up to twice the bunkering space as marine gas oil (MGO). According to MAN engines, the corrosive characteristics and formaldehyde generation of methanol fuel can be easily solved in the currently operated two- and four-stroke marine diesel engines. A dual-fuel engine with 89% methanol and 11% marine diesel oil will comply with the required IMO emission regulations and would generate reductions in NO_X, SO_X, CO, CO_2 and PM emissions of 76.78%, 89%, 97%, 18.13%, and 82.56%, respectively. Since the methanol molecule contains no carbon-carbon bonds, it does not produce particulate matter or soot when burned, resulting in smokeless operation. [37] [38] [39]

According to gas/particle partitioning of semi-volatile organic compounds in the atmosphere[40], methanol, which has a vapor pressure of 127 mm Hg at 25˚C,[41] is expected to exist solely as a vapor in the ambient atmosphere. Vapor-phase methanol is degraded in the atmosphere by reaction with photo-chemically-produced hydroxyl radicals; the half-life for this reaction in air is estimated to be several hours.[42] Methanol vapor has no GWP value. The major degradation product from reaction with hydroxyl radicals is formaldehyde[43]. In the air, formaldehyde breaks down in sunlight to form carbon monoxide in approximately one hour.[44]

METHANOL VESSEL CONSIDERATIONS

Methanol's specific energy of 19.9 MJ/kg is much lower than that of LNG yet has roughly about half the storage density to LNG when considering its pressurized and/or refrigerated tanks, etc.

Methanol is a liquid at atmospheric pressure between -93°C and 65°C, making storage less expensive when compared to LNG. Given specific energy densities and space requirements for storage, methanol and LNG are similar in terms of effective energy density.

Methanol-fueled new builds also cost less than an LNG ship, according to engine builders MAN Energy Solutions and Wärtsilä. Kjeld Aabo, Director New Technology's two-stroke promotion, MAN Energy Solutions, stated that a 54,300m^3 capacity product tanker with methanol-fueled engines adds about 10% to new build price. The same vessel running on LNG would cost 22% more.[45] MAN, which first unveiled and tested a methanol dual-fuel engine in 2016 and has a current order book of 23 ME-LGIM™ engines,[46] says methanol emits 8% less CO_2 than an HFO Tier II engine.

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[37] N Ammar "An environmental and economic analysis of methanol fuel for a cellular container ship" Transport and Environment, Volume 69, 2019, Pages 66-76, doi.org/10.1016/j.trd.2019.02.001.

[38] F. Murena et al."Impact on air quality of cruise ship emissions in Naples, Italy" Atmos. Environ. (2018)

[39] B. Dragović et al. "Ship emissions and their externalities in cruise ports" Transp. Res. Part D: Transp. Environ. (2018)

[40] Bidleman TF; Environ Sci Technol 22: 361-367 (1988).

[41] Boublik T et al, eds; The Vapour Pressures of Pure Substances. 2nd rev ed. Amsterdam: Elsevier p. 57 (1984).

[42] Atkinson R et al; Atmos Chem Phys 6: 3625-4055 (2006)

[43] Grosjean D; J Braz Chem Soc 8: 433-442 (1997).

[44] D Kaden, C Mandin, G Nielsen, and Wolkoff, "WHO Guidelines for Indoor Air Quality", 2010. https://www.ncbi.nlm.nih.gov/books/NBK138711/

[45] "Methanol-fueled ships less costly to build and operate than those burning LNG" Pollution Solutions, Aug 02 2021 https://www.pollutionsolutions-online.com/news/air-clean-up/16/seabornecomms/methanol-fuelled-ships-less-costly-to-build-and-operate-than-those-burning-lng/55830

[46] The MAN B&W ME-LGIM engine is a dual-fuel methanol injected engine.

MAN Energy Solutions developed the ME-LGIM™ dual-fuel engine for operation on methanol, heavy fuel oil (HFO), MDO, or MGO. The engine is based on the company's proven ME-series, with its approximately 5,000 engines in service, and works according to the Diesel principle as methanol is a low-flashpoint, liquid fuel. When operating on methanol, the ME-LGI uses HFO, MDO, or MGO as a pilot fuel, significantly reduces emissions of CO_2, NO_X and SO_X, and methanol slip. Additionally, any operational switch between methanol and other fuels is seamless. Tests on the engine, when running on methanol, have recorded the same or a slightly better efficiency compared to conventional HFO-burning engines.

Wärtsilä introduced a methanol engine in in 2013 based upon the model 32 with over 5,300 engines installed. Toni Stojcevski, Wärtsilä General Manager, Project Sales & Development, revealed that the engine builder expects to have a new version of a methanol-burning engine based on its proven W32 series in late 2023 available for new builds and retrofit.

The procedure of installing a methanol engine can be made through either building a new ship with a clean installation or as a conversion of the old engine. The conversion of the old engine is completed by replacing the cylinder head for a Liquide Gas Injection type (LGI), adding the double walled piping, a new monitor system and installing a new ventilation system for the fuel pipes. This conversion is called retrofit and can be performed to all of the existing two-stroke crosshead engines that MAN delivers. The retrofit will not affect the performance of the engine specification more than higher fuel consumption because of the lower heating value of methanol compared to diesel or HFO. Because methanol is a low flashpoint fuel there must be a ventilation system installed to prevent any leakage from entering the engine room atmosphere.

This ventilation system is combined with double walled piping which is installed to all piping within the engine room. If there is to be a leakage of the fuel from the primary pipe it will be leaking into the next pipe, the fuel fumes will be transported by the pipe ventilation to a gas detector. If any methanol fumes are detected the system will automatically shut of the methanol supply and switch over to full diesel operation. To retrofit a diesel-powered vessel to run on methanol, the cost will be about the same as installing the systems for methanol power for a new constructed ship at the shipyard.

CONCLUSION

When considering whether to transition to methanol or LNG, the following need to be considered:

- CO_2e footprint of Blue Methanol is 5–10% lower than LNG, combining well-to-gate production footprint and hull-to-wake consumption footprint.
- Methanol fuel costs are less volatile than LNG, and today, methanol is roughly half the cost.
- A methanol-fueled engine adds ≈10% to the cost of a new vessel, LNG engine adds 22% more.
- Methanol is easier to handle and store than LNG, with half the bunkering time.
- Methanol bunkering infrastructure is easier and cheaper than LNG bunkering infrastructure.
- Path to a carbon-neutral methanol fuel is being developed, but no path exists for LNG.