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Comprehensive review of methanol and LNG as alternative fuels for marine diesel engines

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The maritime sector is undergoing a critical transition driven by increasingly stringent emissions regulations from the International Maritime Organization (IMO) and the European Commission (EC). Among the leading alternative fuels for marine diesel engines, methanol and liquefied natural gas (LNG) have gained significant attention. This review synthesizes recent research and industry data to compare the two fuels across physico-chemical properties, combustion performance, emission behavior, safety, and economic feasibility. Methanol, a liquid under ambient conditions, enables easier storage and refueling using existing liquid-fuel infrastructure while providing substantial reductions in sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) emissions. However, its low energy density and the formation of formaldehyde remain drawbacks. In contrast, LNG offers higher volumetric energy density and immediate reductions in carbon dioxide (CO_2), SO_x, and NO_x emissions but requires expensive cryogenic storage systems and faces the persistent challenge of methane slip. Economically, LNG engines entail higher capital investment yet support short-term regulatory compliance, whereas renewable methanol offers a scalable pathway toward long-term carbon neutrality. Overall, the optimal choice between methanol and LNG depends on operational profiles and strategic objectives, with LNG serving as a transitional solution and methanol representing a flexible, future-proof option for sustainable marine propulsion.

Key words: *methanol, liquefied natural gas, alternative fuels, marine diesel engines, decarbonization*

1. Introduction

The global maritime industry stands at an important juncture. As international trade volumes continue to expand, the sector faces growing scrutiny over its environmental footprint. Shipping is responsible for approximately 3% of global anthropogenic CO_2 emissions and contributes a substantial share of global NO_x (≈ 15%) and SO_x (≈ 4–9%) emissions [38, 53, 96, 141]. These pollutants are now recognized as major contributors to both climate change and regional air quality degradation, driving international policy reform. The IMO and the EC have therefore introduced increasingly stringent measures to decarbonize maritime transport, including the IMO's 2023 Greenhouse Gas (GHG) Strategy, the Carbon Intensity Indicator (CII) framework, and the extension of the European Union (EU) Emissions Trading System (ETS) to the shipping sector [4, 17, 31, 33, 136, 182]. The IMO's 2023 GHG Strategy for shipping sets an ambition for the sector to reduce carbon intensity by at least 40% by 2030 (vs 2008) and to achieve net-zero greenhouse-gas emissions by or around 2050. Meanwhile, the EU's FuelEU Maritime Regulation (Regulation (EU) 2023/1805) mandates the use of renewable and low-carbon fuels on board ships calling at EU ports from 1 January 2025 [30, 31, 33, 44, 110].

Conventional marine fuels such as heavy fuel oil (HFO) and marine diesel oil (MDO) have long dominated the sector due to their low cost and established infrastructure, but they have been increasingly criticized for their contribution to air pollution and climate change [20, 115, 159]. The combustion of these fuels releases high levels of SO_x, NO_x, CO_2, and particulate matter (PM), leading to both local air-quality degradation and global warming impacts [45, 71, 134, 150]. Consequently, identifying and adopting alternative marine fuels that can ensure energy security, regulatory compliance, and long-term sustainability has become a strategic priority across the maritime industry [20, 27, 51].

A broad spectrum of alternative energy carriers has been proposed, including hydrogen, ammonia, biofuels, LNG, and methanol, as well as emerging options such as synthetic (e-)fuels and hybrid-electric systems [20, 123, 179]. Each pathway offers unique advantages and challenges in terms of energy density, handling safety, storage requirements, infrastructure availability, and overall lifecycle emissions [94, 166]. However, among these options, LNG and methanol have emerged as the most technically mature and commercially deployable alternatives for near- and medium-term adoption in the maritime sector [121, 179].

While hydrogen and ammonia offer significant decarbonization potential, their storage complexities, toxicity risks, and limited infrastructure pose major barriers to large-scale deployment in the current decade [103, 155, 156]. Similarly, biofuels face challenges of feedstock sustainability, cost volatility, and an uncertain lifecycle emissions-reduction potential [20, 80, 107]. In contrast, LNG and methanol occupy a pragmatic middle ground – they are compatible with current engine technology and logistics, can be produced from both fossil and renewable sources, and are supported by established industrial supply chains. Their comparative readiness makes them strong candidates for transitional and early-adopter decarbonization strategies under the IMO's 2030 and 2050 frameworks [20, 94, 123, 179].

However, despite growing deployment, the two fuels embody fundamentally different decarbonization philosophies. LNG offers an incremental, bridge-fuel approach, providing immediate reductions in SO_x, NO_x, and PM, albeit constrained by methane slip and upstream leakage [8, 10, 56, 69, 154]. Methanol, conversely, presents a transformational long-term solution, capable of achieving near-zero life-cycle emissions when produced from renewable hydrogen and captured CO_2 ("green" methanol) [5, 20, 40, 105].

The literature contains numerous studies addressing either LNG or methanol independently. However, a unified comparative review that synthesizes the latest data on performance, lifecycle emissions, safety, infrastructure, and economics, particularly for dual-fuel (DF) marine diesel engines, remains limited. This paper addresses that gap by providing a comprehensive, integrative analysis of both fuels, combining recent findings from peer-reviewed literature, life-cycle assessments (LCAs), and industry data. It aims to clarify the relative advantages, trade-offs, and strategic implications of choosing between LNG and methanol as alternative fuels for diesel engines, and to identify key research needs for supporting the maritime sector's ongoing transition toward carbon neutrality.

2. Methodology

2.1. Search strategy and information sources

This review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. Literature searches were conducted on 15 September 2025 across three major databases: Scopus, Web of Science Core Collection, and ScienceDirect. The search covered the period from January 2010 to September 2025 and was limited to English-language, peer-reviewed journal papers.

Exact search strings:

Scopus:

TITLE-ABS-KEY(("methanol" OR "liquefied natural gas" OR LNG) AND ("marine fuel" OR "ship" OR "diesel engine" OR "dual-fuel") AND ("emission" OR "performance" OR "life cycle" OR "LCA" OR "well-to-wake"))

Web of Science:

TS=(("methanol" OR "liquefied natural gas" OR LNG) AND ("marine fuel" OR "shipping" OR "dual-fuel engine") AND ("emission" OR "LCA" OR "life-cycle" OR "efficiency"))

ScienceDirect:

"methanol" OR "LNG" AND ("marine fuel" OR "dual-fuel engine") AND ("emission" OR "LCA" OR "performance") in Title, Abstract, Keywords.

Manual searches of Energy Conversion and Management, Fuel, Journal of Marine Engineering & Technology, Journal of Marine Science and Engineering, and Applied Energy were also performed to capture in-press or early-view articles. Reference lists of key papers were hand-checked to identify additional studies.

2.2. Eligibility criteria (PICO framework)

The review used the PICO framework to identify publications. In which:

- Population (P): Marine diesel or DF engines and ship propulsion systems
- Intervention (I): Operation using methanol or liquefied natural gas (LNG) as an alternative or DF
- Comparison (C): Conventional marine diesel oil (MDO), and heavy fuel oil (HFO)
- Outcomes (O): Engine performance (BTE, power output), regulated and unregulated emissions, well-to-wake (WtW) greenhouse-gas emissions, techno-economic metrics, and safety or infrastructure aspects.

Only peer-reviewed original research and review articles providing experimental, numerical, or life-cycle-based data were included. Exclusion criteria comprised: (a) conference abstracts without full text, (b) non-English papers, (c) studies lacking clear methodology or quantitative results, (d) conceptual opinion papers, and (e) non-marine or unrelated power applications.

2.3. Screening and selection protocol

All retrieved records (n = 523) were imported into EndNote X21 for de-duplication, leaving n = 412 unique records. Two independent reviewers screened titles and abstracts. Disagreements were resolved by discussion with a third reviewer. During title and abstract screening, 288 records were excluded for the following reasons: out of scope (n = 156), non-English language (n = 42), conference abstracts without full text (n = 47), and studies lacking quantitative engine or LCA data (n = 43). After initial screening, 124 full-text papers were evaluated for eligibility. Finally, 48 studies were included in the qualitative synthesis, and 36 in the quantitative comparison. The PRISMA 2020 flow diagram summarizing identification, screening, eligibility, and inclusion is shown in Fig. 1.

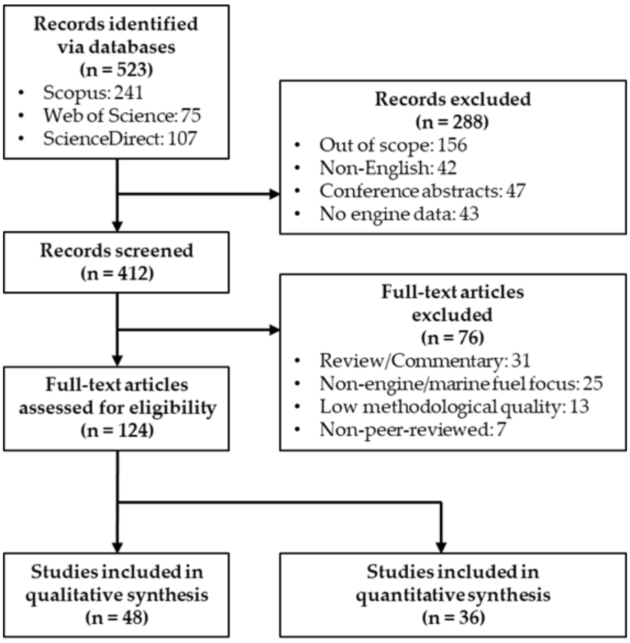

Fig. 1. PRISMA 2020 flow diagram

2.4. Quality evaluation and data extraction

Each included study underwent methodological quality assessment using the Critical Appraisal Skills Program (CASP) checklist for quantitative studies, complemented by ROBINS-I for risk-of-bias evaluation where applicable. Scores were assigned on a 10-point scale; papers scoring < 6 were excluded from quantitative synthesis but discussed qualitatively.

Key variables extracted included: fuel type and properties, engine configuration and operating conditions, emission metrics (CO_2, CH_4, NO_x, SO_x, PM, aldehydes), LCA boundary assumptions, and techno-economic indicators (CAPEX, retrofit cost, fuel price). Extraction was performed independently by two reviewers using standardized forms to ensure consistency.

3. Fuel properties and characteristics

3.1. Properties of methanol (CH_3OH)

Methanol is a colorless, volatile liquid with a faintly sweet, alcohol-like odor and is completely miscible with water [158]. One of its most notable characteristics is its low energy density. By weight, it has an energy density of approximately 22 MJ/kg, and by volume, this figure is only 15.7 MJ/L [128, 187]. This means that methanol has a significantly lower energy density than both diesel and LNG.

In terms of combustion properties, methanol has a very low cetane number (below 5) and a high octane number (109), making it unsuitable for direct use in conventional compression-ignition engines (CIEs). Another property to note is that methanol burns with a faint, nearly invisible blue flame that produces no smoke or soot [158, 187].

3.2. Properties of LNG

LNG is natural gas, primarily methane (CH_4), that has been cooled to an extremely low temperature of approximately −162°C to convert it to a liquid. This process reduces its volume to about 1/600th of its gaseous state. In its liquid state, LNG is colorless, odorless, non-corrosive, and non-toxic [82, 130, 151].

LNG has a higher energy density than methanol, with a volumetric density of 23.4 MJ/L. By weight, it has an energy density of 53.6-55 MJ/kg [185]. A critical parameter for LNG is the Methane Number (MN). This parameter indicates a fuel's resistance to knocking in an engine; a higher MN value (above 80) indicates better fuel quality and optimized engine performance. The MN is highly dependent on the composition of the LNG. In which "heavy LNG" (with a higher content of ethane and propane) has a lower MN than "light LNG" (with a higher methane content) [84].

3.3. Synthesis of fuel characteristics

A fundamental difference between these two fuels lies in the trade-off between volumetric energy density and handling complexity. As mentioned, methanol has a lower energy density than both LNG and diesel [117, 132]. This directly results in the need for larger storage tanks to achieve the same operating range. However, methanol is a liquid at ambient temperature and pressure, allowing it to be handled and stored similarly to conventional fuels, though with safety and corrosion considerations [68].

Conversely, LNG's higher energy density is tied to its cryogenic state. This requires specialized, highly insulated storage systems that are more complex and expensive. LNG's higher energy density, an advantage, is offset by the complexity of cryogenic storage, a major disadvantage. Meanwhile, methanol's low energy density, a disadvantage, is offset by its simple physical state, a major advantage. This is not just a list of facts but a fundamental, causal trade-off that affects design, cost, and logistics [6, 52, 165]. A comparison of the physical and chemical properties of methanol and LNG is presented in Table 1.

Table 1. Comparison of methanol and LNG physical and chemical properties

Property	Methanol (CH_3OH)	LNG (Primarily CH_4)
Physical state	Liquid (at ambient temp. & pressure) [173]	Cryogenic Liquid (at approx. −162°C) [101, 130]
Energy density (MJ/L)	15.7 [158, 187]	23.4 [185]
Energy density (MJ/kg)	22 [158, 187]	53.6–55 [185]
Cetane number	< 5 [158, 187]	N/A (requires methane number) [84]
Octane number	109 [158, 187]	> 120 [13]
Flash point	12°C [108]	−188°C (volatile) [148]
Flame characteristics	Invisible, blue flame [108]	Visible when burning [133]

4. Engine technology and performance

4.1. Methanol DF engine systems

Methanol has a very low cetane number, which means it cannot self-ignite in a traditional diesel compression-ignition cycle [59, 178]. Therefore, its combustion requires a catalyst, most commonly a small amount of diesel fuel in a pilot injection system [39].

DF technologies, such as High-Pressure Direct Injection (HPDI), work by injecting a small amount of diesel to initiate combustion, which raises the temperature and pressure inside the cylinder, followed by the injection of methanol into the combusting mixture [90, 118, 137, 161-164, 175, 186]. Other injection strategies have been proposed and tested to optimize performance and reduce knocking, including injecting methanol before or after the diesel injection, or even in a split-injection mode [97].

Existing engine conversion solutions are available from major manufacturers such as Wärtsilä and Everllence (formerly MAN B&W). These conversions require the addition of new components and double-walled piping systems to ensure safety [39]. Real-world projects have demonstrated the successful conversion of small tugboats and large container vessels to run on methanol [32].

4.2. LNG DF engine systems

LNG can be used in two main types of engines: Low-Pressure Dual-Fuel (LPDF, Otto-cycle premixed combustion) engines and High-Pressure Dual-Fuel (HPDF, based on high-pressure direct injection – HPDI) [18, 79, 127, 131]. HPDF, often referred to as the Diesel-cycle engines, is becoming increasingly popular in heavy-duty applications. Similar to methanol, the HPDI system utilizes a small amount of diesel (approximately 5% of the total fuel volume) as a "liquid spark plug" to initiate combustion [18, 79, 127, 129, 131].

However, converting a diesel engine to run on LNG often requires a "complete overhaul" [13, 34, 109, 114]. This involves fundamental mechanical changes, such as modifying pistons to lower the compression ratio and installing spark plugs, modifying injection systems, adding a gas supply, and installing safety systems, particularly for Otto cycle engines [13, 18, 34, 79, 109, 114, 131]. The system also requires a high-pressure cryogenic pump to convert low-pressure liquid LNG into a high-pressure gas ready for injection [72, 79]. Table 2 summarizes the key technical and strategic differences between methanol- and LNG-fueled marine engine systems.

Table 2. Conceptual comparison of methanol and LNG dual-fuel marine engine systems

Aspect	Methanol D) engine	LNG DF engine
Fuel Physical State	Liquid at ambient temperature and pressure	Cryogenic liquid (approx. −162°C)
Onboard Storage	Non-pressurized tanks; conventional liquid-fuel storage with material compatibility measures	Cryogenic Type C insulated tanks; vacuum insulation; boil-off management
Fuel Supply System	Low-pressure liquid fuel supply; double-walled piping; leak detection systems	Cryogenic pumps, vaporizers, high-pressure gas lines; insulated piping
Injection Strategy	Diesel pilot injection + direct methanol injection	Diesel pilot injection + high-pressure gas injection (HPDF) or low-pressure premixed injection (LPDF)
Combustion Mode	Compression-ignition (CI)-based dual-fuel operation	HPDF: Diesel-cycle stratified combustion; LPDF: Otto-cycle premixed combustion
Engine Modification Level	Incremental retrofit; addition of fuel system and safety components	Major modification or complete overhaul (especially LPDF conversions)
Brake Thermal Efficiency (Typical Range)	approx. 40–46% (optimized high-load operation may exceed diesel baseline)	HPDF: approx. 44–46% (diesel-like); LPDF: approx. 38–44% depending on load
Tank-to-Wake Emission Characteristics	SOx: approx. 99% reduction; PM: approx. 95–99% reduction; NO_x: approx. 40–80% reduction; possible increase in aldehydes (formaldehyde)	SOx: approx. 100% reduction; PM: approx. 100% reduction; NO_x: approx. 80–90% reduction; methane slip possible
Well-to-Wake Climate Performance	Grey methanol: may exceed diesel CO_2e; Green methanol: approx. 50–70% reduction	HPDF LNG: approx. 15–23% reduction; performance sensitive to methane slip
Infrastructure Requirements	Compatible with existing liquid-fuel logistics; simpler bunkering	Requires cryogenic infrastructure; complex bunkering procedures
Safety Profile	Toxicity risk; low flash point; invisible flame; requires containment and gas detection	Cryogenic hazards; vapor cloud explosion risk; methane-air flammability (5–15%)
Strategic Decarbonization Role	Long-term pathway toward carbon neutrality via green methanol	Transitional “bridge fuel”; near-term regulatory compliance advantage

4.3. Performance and efficiency

Methanol-fueled engines can achieve high brake thermal efficiency (BTE), even outperforming the original diesel engine under certain conditions, thanks to their high octane number and high heat of vaporization. Guo et al. reported that a marine DF engine with approx. 90% methanol energy fraction, with methanol injection at approx. 80°CA (crank angle) BTDC (before top dead center) and diesel pilot at approx. 12°CA BTDC, has thermal efficiencies of about 46% at high loads, approx. 45% at medium, and approx. 43% at low loads. The study highlights that thoughtful timing and injection strategies can leverage methanol’s characteristics (e.g., heat of vaporization, etc.) to approach or exceed diesel-mode efficiency in many load cases [58]. Karvounis et al. noted that methanol’s high latent heat of vaporization reduces in-cylinder temperatures, thereby reducing heat losses and, under some conditions, improving indicated or BTE [77]. Lebedevas and Milašius reported that the marine engine cycle modeling with approx. 95% methanol injected (direct injection) alongside a diesel pilot, under optimized conditions, produced an approx. 4.2% higher thermal efficiency compared to diesel in that mode [91]. Liu et al. showed that methanol, when used in high-compression-ratio engines, has the potential to achieve high indicated efficiency. Methanol’s latent heat of vaporization is approx. 2.6 times higher than that of diesel per unit mass, which cools the intake charge and lowers the in-cylinder temperatures, which reduces heat transfer losses [99]. Pu et al. mentioned that methanol engines (including turbocharged and high-compression concepts) reach very high thermal efficiencies. The review reported a peak BTE of approx. 43% in a turbocharged engine with a compression ratio (CR) of 19.5. The authors explicitly connect such high efficiencies to operation strategies that exploit methanol’s high octane and strong charge-cooling (high latent heat) to enable advanced phasing and lean/low-temperature combustion modes [132]. Treacy et al. reported in [153] that under optimized intake temperature, injection timing and higher CR, methanol direct-injection (DI) compression-ignition (CI) operation can achieve competitive indicated/thermal efficiency. The paper emphasizes the latent heat and mixing/auto-ignition roles of methanol, as well as the need for intake preheating to stabilize combustion. This explains how high heat of vaporization cools the intake/charge air, enabling favorable combustion phasing and reduced heat losses. Karvounis et al. summarized that many bench studies have shown that methanol, when used in partial- or DI strategies, increases BTE under medium-to-high loads when injection timing, CR, and intake temperature are optimized. They review and attribute efficiency gains to methanol’s higher resistance to knock (high RON/RON-like behavior in premixed strategies) and its charge-cooling effect, which reduces combustion/heat losses [77]. A single-cylinder experimental work reported a net fuel conversion efficiency of approx. 42.5% for methanol in a high-compression research engine under stoichiometric/controlled conditions. The efficiency of methanol in this study is higher than several alternative fuels tested. The study results demonstrate practical efficiency benefits traceable to methanol’s favorable knock resistance (allowing higher compression) and its cooling during vaporization, which alters heat transfer/loss profiles [49]. An experimental and parametric study on a marine engine showed that optimized methanol injection timing and injection strategy (single-point vs multi-point) produced BTE increases up to approx.4–5% relative to diesel-only operation in certain configurations. The authors explicitly link the

BTE gains to phasing changes enabled by methanol properties (cooling during vaporization that reduces heat loss and high knock resistance) [58]. However, some studies have shown a slight decrease in engine performance (power output) with methanol blends, offset by a significant reduction in emissions. Hassan et al. showed that low-to-moderate methanol blends can reduce peak power slightly while lowering carbon monoxide (CO), unburnt hydrocarbon (uHC), and soot, and improving brake-specific fuel consumption (BSFC) at many operating points [60]. Kadhim et al. reported measurable reductions in CO, uHC, and PM with increasing methanol fraction, along with small reductions in power output at some loads [74]. Vișan et al. showed that methanol/biofuel blends can cause a few percent decrease in brake effective power relative to pure diesel while substantially reducing particulate and uHC emissions [160]. Vargün et al. reported slight reductions in peak power with methanol addition in some blends, coupled with reduced PM and CO emissions and mixed NO$_x$ response depending on operating point [157].

Regarding LNG-fueled engines, the HPDI system in HPDF engines that injects gaseous fuel at high pressure near top dead center (TDC), producing diesel-like stratified combustion but with NG as the primary fuel. This preserves the diesel combustion phasing and in-cylinder thermodynamics that give diesel its high BTE. Recent experimental and review studies report that HPDF engines achieve thermal efficiencies similar to those of diesel engines. The HPDF concept is explicitly shown to approach diesel BTE while keeping the emissions benefits of gaseous fuels [28]. Babayev et al. reported in a numerical study that HPDF preserves diesel-like thermodynamic behavior and can achieve high thermal efficiency with appropriate injection/combustion phasing [14]. Recent review of new DF combustion modes (pre-chamber-ignited HPDF, premixed stratified, etc.) concluded that PI-HPDF and related high-pressure concepts can achieve diesel-like BTE while reducing PM and SO$_x$ [23]. Zhang et al. reported that advancing pilot diesel injection timing increases power and thermal efficiency in a pilot-ignited NG engine, but also affects NO$_x$ and CH$_4$ slip [183]. Wei et al. reported that split/high-pressure injection strategies can optimize heat release and increase BTE in NG HPDF engines while reducing methane slip [170].

Meanwhile, the LPDF and port-injection DF systems, in which gas is supplied at low pressure and premixed with intake air, result in more premixed combustion and can shift heat release earlier, sometimes increasing knock/uHC or requiring pilot diesel for ignition. The efficiency depends strongly on load and gas fraction. Several reviews and field studies show LPDF engines often have somewhat lower BTE at low loads or at high gas substitution, though at medium–high loads, efficiency can be near diesel if optimized. A comparative analysis shows that LPDF and port-injection systems are simpler but often show lower BTE at part load than HPDF [22]. Overall, HPDF tends to show the best chance of matching diesel [124, 149].

The conversion of diesel engines to LNG has many differences compared to methanol. The literature consistently describes converting diesel engines to LNG-fueled engines as a "complete overhaul", involving fundamental mechanical changes such as piston modification and the addition of spark plugs. This implies a more complex and costly process [21, 50, 73, 106, 146, 152]. In contrast, methanol conversions are described as "retrofit solutions" and the "addition of components" to the existing diesel cycle [167].

Table 3. Comparative performance and thermal efficiency of methanol- and LNG-fueled engines

Fuel	Engine configuration/ operating mode	Typical BTE [%]	Performance characteristics and key observations	References
Methanol	DF marine engine (≈90% methanol, diesel pilot)	High load: 46%; Med. load: 45%; Low load: 43%	Optimized methanol injection (~80°CA BTDC) and pilot diesel (~12°CA BTDC) achieve BTE approaching or exceeding diesel at all loads. High octane and strong charge-cooling enable efficient combustion phasing.	[58]
	DI DF marine engine (≈95% methanol, pilot diesel)	Increase 4.2% vs. diesel	Modeling shows ~4.2% higher cycle efficiency vs. diesel due to optimized combustion phasing and methanol's latent heat.	[91]
	Turbocharged methanol engine (CR ≈19.5)	approx. 43%	High compression ratio and turbocharging leverage methanol's charge-cooling and knock resistance; high efficiency under lean operation.	[132]
	High-compression research engine (stoichiometric DI)	approx. 42.5%	Methanol exhibits higher efficiency than other tested fuels due to reduced heat losses and favorable autoignition control.	[49]
	General DF/DI strategies (medium–high load)	40–46%	Methanol's high latent heat reduces in-cylinder temperatures and heat transfer losses; injection timing and CR strongly influence BTE.	[58, 77, 99, 153]
	Blended operation (methanol–diesel or methanol–biofuel)	Slightly reduced power (–1–3%)	Small reduction in power output offset by improved BSFC, lower CO, uHC, and PM emissions.	[60, 74, 157, 160]
LNG (high-pressure)	HPDI (high-pressure direct injection) DF engine	44–46% (≈Diesel)	Maintains diesel-like combustion and thermodynamic cycle; high efficiency with diesel pilot ignition and late high-pressure gas injection; low PM/SOx.	[14, 23, 28, 170, 183]
	Pre-chamber or stratified HPDI concepts	43–45%	Advanced HPDI and PI-HPDI systems achieve near-diesel BTE with lower soot and improved combustion control.	[14, 23]
	HPDI with split/advanced injection	Increase 1–2% over baseline	Optimized injection strategies improve heat release, enhance BTE, and reduce CH_4 slip.	[170, 183]
LNG (low-pressure)	LPDF/port-injection DF engine	38–44%	Simpler system, lower pressure, higher substitution possible, but lower BTE at part load due to earlier heat release and incomplete combustion at high gas fractions.	[22, 124, 149]
	Complete overhaul or spark-ignited conversions	–	Requires complete mechanical overhaul (spark plugs, piston redesign). Higher complexity and cost than methanol retrofit.	[21, 50, 73, 106, 146, 152]

This suggests that an LNG conversion requires a fundamental shift in the engine's operating principle (from compression-ignition to spark-ignition), whereas a methanol conversion is an incremental modification to the existing diesel combustion process [35, 39, 83, 184]. This difference has direct implications for the capital cost, downtime, and technical complexity of a conversion project. A comparative performance and thermal efficiency of methanol- and LNG-fueled engines is presented in Table 3.

5. Environmental and emission profile

5.1. Tank-to-wake emissions

Methanol combustion is extremely clean. It significantly reduces SO_x emissions by up to 99%, NO_x by up to 60%, and PM by up to 95% compared to conventional fuels [9, 111]. Parris et al. also reported in [123] that methanol dramatically reduces SO_x (up to approx. 99%) and PM (up to approx. 95%), while NO_x is reduced by up to approx. 80% compared to HFOs. Methanol Institute reported the same tendency [66]. Aakko-Saksa et al. stated that methanol and LNG yield near-complete elimination of SO_x and large reductions in PM compared to HFO/MDO, and provide comparative ranges for NO_x benefits [2]. IMO reported in GreenVoyage2050 that methanol can achieve approx. 92–99% SO_x reduction, approx. 55% NO_x reduction (lifecycle average), and very large PM reductions when replacing HFO/MDO [64].

Multiple experimental and numerical studies reported that methanol combustion tends to produce higher levels of unregulated aldehydes (notably formaldehyde) and other partial-oxidation products than conventional hydrocarbon fuels [169, 171]. Methanol oxidation proceeds through partial-oxidation intermediates ($CH_3OH \rightarrow HCHO \rightarrow HCOOH \rightarrow CO/CO_2$). Under engine conditions, especially in quench zones, crevices, or regions with short residence time / low local temperature, oxidation can stop at formaldehyde, which is less oxidized and can be emitted. Crevice/quenching and incomplete mixing effects (and certain low-temperature or lean-combustion modes) increase the fraction of formaldehyde escaping the cylinder [102]. Williams et al. reported that formaldehyde is the dominant aldehyde emitted from methanol combustion and that HCHO emissions are substantially higher when methanol (or methanol blends) are used compared with gasoline [172]. Ma et al. reported in [102] that formaldehyde forms in crevice/quench regions and can be emitted. Chao et al. showed that adding methanol to diesel can increase formaldehyde emissions by up to 4.5 times at low engine loads [26]. A summary of the emission-reduction effectiveness of methanol and LNG compared with conventional marine fuels is presented in Tables 4 and 5, respectively.

Regarding LNG, multiple studies and real-world measurements show that LNG combustion can reduce SO_2 and PM emissions by nearly 100% relative to MDO and yield NO_x reductions of 80–90% [2, 62, 100, 116]. Aakko-Saksa et al. reported that LNG-fueled ships have demonstrated nearly complete elimination of SO_x and PM emissions and approx. 90% reduction in NO_x compared to conventional marine fuel oil engines [2]. Lebedevas et al. stated that switching from diesel to LNG fuel resulted in the reduction of SO_2 by approx. 91% and NO_x by 65%, while CO_2 decreased by about 23% [92]. Anderson et al. reported that LNG operation resulted in near elimination of sulfur and particulate emissions and an approx. 85–90% reduction in NO_x relative to HFO [10].

Table 4. Summary of methanol's emission reduction effectiveness in comparison to conventional marine fuels (HFO/MDO)

Pollutant	Max/typical reductions	References
SO_x	approx. 92–99%	[64, 66]
PM	approx. 90–99%	[48, 66]
NO_x	approx. 40–60%	[2, 64]

Table 5. Summary of LNG's emission reduction effectiveness in comparison to conventional marine fuels

Researchers	NO_x reduction	SO_x reduction	PM reduction	References
Livaniou et al.	83.7%	approx. 100%	approx. 100%	[100]
Aakko-Saksa et al.	approx. 90%	approx. 100%	approx. 100%	[2]
Lebedevas et al.	65%	91%	—	[92]
Anderson et al.	85–90%	approx. 100%	approx. 100%	[10]
Heikkilä et al.	88%	99%	97%	[62]

5.2. Well-to-wake emissions

While both methanol and LNG are cleaner than diesel, they each pose unique challenges regarding non-CO_2 emissions. For methanol, it is the increase in unregulated aldehyde emissions [26, 102, 169, 171, 172]. For LNG, it is "methane slip", the leakage of unburned methane from the engine exhaust. Of these, methane slip is the more concerning issue.

Methane is a potent GHG, with a Global Warming Potential (GWP) of up to 28–36 times that of CO_2 over a 100-year timescale ($GWP_{100} = 28–36$) [16, 78]. Methane slip is increasingly recognized as a major challenge for realizing the climate benefits of LNG in marine propulsion [12, 61, 70, 85-89, 139, 154, 176, 181]. Methane slip is particularly concerning for LPDF engines and at low engine loads (e.g., in port or during maneuvering). Multiple onboard studies reported that methane slip rises sharply at low engine loads. Engine load monitoring on a RoPax vessel with an LPDF engine measured a yearly average fuel-slip coefficient of approx. 1.57% [142]. The primary causes identified are incomplete combustion due to low-pressure injection or poor mixing, quenching or crevice-volume losses, and low temperatures [95]. Mitigation strategies under study include catalytic aftertreatment, design optimizations (reduced crevices, improved injection pressure), and operational measures such as minimizing low-load operation [12, 139, 176, 181]. Unregulated aldehyde and methane slip create a direct trade-off: the choice between a powerful but short-lived GHG (methane) and a pollutant with harmful health effects (formaldehyde). This decision is a choice between global environmental impact and local air pollution.

Another critical difference lies in the decarbonization pathway. Based on analysis from several sources, fossil LNG (often called “grey LNG”) provides an immediate and significant GHG emissions reduction on a WtW basis, up to 23% compared to conventional fossil fuels, especially with high-pressure engines [69, 125]. LNG is widely recognized as a transitional marine fuel capable of delivering measurable WtW GHG reductions compared with conventional marine fuels. The magnitude of this benefit depends strongly on engine technology, operational conditions, and upstream methane management. LCAs have demonstrated that low-speed, high-pressure DF (HPDF) engines, which operate on the Diesel cycle and exhibit minimal methane slip, offer the most substantial WtW GHG reductions, typically in the range of 15–23% relative to very-low-sulfur fuel oil (VLSFO) or MDO [3, 69, 143]. In contrast, LPDF engines can offset these gains through higher unburned methane emissions [3, 125]. The comprehensive industry LCA by Sphera and SEA-LNG [143] reported up to 23% WtW reduction for LNG in HPDF configurations, a finding broadly supported by independent peer-reviewed studies [3, 69]. However, the potential advantage is sensitive to methane slip and upstream leakage, as emphasized by the International Council on Clean Transportation (ICCT) [125], underscoring that the overall climate performance of LNG as a marine fuel hinges on both engine design and methane management across the supply chain.

In contrast, fossil methanol (often called "grey" or "brown" methanol) has a worse WtW CO_2 footprint than diesel, meaning it is not a viable long-term decarbonization solution on its own. Multiple recent LCAs and reviews showed that methanol made from fossil feedstocks (NG or coal) often has higher WtW CO_2e emissions than conventional MDO, because methanol production (steam methane reforming, gas-to-methanol, or coal-to-methanol) is energy-intensive and emits CO_2s upstream; when these upstream emissions are included in a WtW accounting, "grey/brown" methanol can exceed diesel's CO_2e footprint unless low-carbon electricity, carbon capture, or renewable feedstocks are used [56, 93, 126, 140, 180]. Fossil methanol production requires conversion of carbon feedstock to synthesis gas and then to methanol; these steps consume heat and generate CO_2 (and fugitive methane in upstream stages), so that well-to-tank (WtT) emissions are high and may outweigh any modest combustion-phase benefits, producing WtW CO_2e greater than diesel for certain production routes and assumptions [93, 126, 140, 180].

However, "blue" and "green" methanol offer dramatically improved climate performance compared to fossil methanol, provided production is powered by low-carbon energy and/or paired with carbon capture. LCAs show that "green" methanol (bio- or electro-methanol) can reduce WtW GWP_{100} emissions by approximately 50-70% relative to conventional diesel under favorable conditions (e.g., imported "green" methanol offers approx. 66% reduction; local "green" methanol offers approx. 57% reduction) [7, 166]. "Blue" methanol, industrial methanol with upstream CO_2 capture (or using renewable CO_2), delivers moderate improvements over "grey" methanol and diesel, but performance depends heavily on capture rate, feedstock supply, and upstream emissions; in some cases "blue" methanol still falls short of the reductions achievable by "green" methanol [166]. Hence, while "blue" methanol can serve as a transitional pathway, only "green" methanol constitutes a viable long-term decarbonization solution for marine propulsion, assuming scale-up of renewable hydrogen or sustainable biomass use [120].

Although biomethane (bio-LNG) and synthetic methane (e-LNG) can be produced and used as low-carbon marine fuels, multiple techno-economic and life-cycle studies concluded that there is no direct "green-LNG" pathway that is as practical and scalable as "green" methanol. Green (e or bio) methanol benefits from higher synthesis efficiency, a mature synthesis industry, and more favorable economics and scaling potential (power-to-methanol), whereas power-to-methane followed by liquefaction suffers larger conversion losses, higher costs, and greater constraints on sustainable biomass availability for biomethane. Hence, e-/bio-LNG remains less favorable in most near-term decarbonization scenarios [29, 37, 46, 55, 76]. This distinction points to a strategic trade-off. The choice between the two fuels is between immediate benefits (LNG) and a long-term, deep-decarbonization potential that requires a leap of faith in the development of the green supply chain (methanol).

5.3. Emission reduction effectiveness of methanol and LNG compared to conventional marine fuels

Methanol and LNG both demonstrate substantial emission reduction potential compared to conventional marine fuels (HFO and MDO). On a tank-to-wake (TtW) basis, methanol offers nearly complete elimination of SO_x emissions (~ 99%) and significant reductions in PM (~ 95%) and NO_x (~ 55–80%), owing to its sulfur-free composition and oxygenated nature, which promote more complete combustion [2, 9, 64, 66, 111, 123]. However, methanol combustion tends to form unregulated aldehydes (particularly formaldehyde) through partial oxidation pathways ($CH_3OH \rightarrow HCHO \rightarrow HCOOH \rightarrow CO/CO_2$), especially under low-temperature or quench-zone conditions [26, 102, 169, 171, 172]. LNG, in contrast, also yields near-total elimination of SO_x and PM emissions and achieves 80–90% reductions in NO_x due to its clean-burning characteristics and high hydrogen-to-carbon ratio [2, 10, 62, 92, 100, 116].

On a WtW basis, fossil LNG ("grey" LNG) offers an immediate and measurable GHG reduction potential of up to approx. 23% relative to conventional fuels, particularly in HPDF Diesel-cycle engines with minimal methane slip [3, 69, 124, 143]. However, methane slip from LPDF engines, especially under low load conditions, can partially or completely offset these gains [12, 61, 70, 85-89, 95, 139, 142, 154, 176, 181]. Fossil methanol ("grey" or "brown" methanol) generally exhibits a higher WtW CO_2e than diesel, mainly due to the CO_2-intensive upstream reforming and synthesis processes [56, 93, 126, 140, 180]. Conversely, "blue" methanol (fossil-based methanol with carbon capture) and "green" methanol (bio- or electro-methanol from renewable sources) offer substantial WtW emission reductions—approx. 50–70% lower than diesel, depending on feedstock and energy source [7, 120, 166]. In contrast, bio-LNG and e-LNG pathways exist but remain less favorable due to higher conversion losses and costs, with limited scalability compared to methanol-based alternatives [29, 37, 46, 55, 76]. The comparative emission profile of methanol and LNG is presented in Table 6.

Table 6. Comparative emission profile of methanol and LNG

Fuel	Emission category	Reduction vs. HFO/MDO	Key characteristics	Main challenges	References
Methanol (TtW)	SO_x	approx. 99% reduction	Sulfur-free fuel	—	[2, 9, 64, 66, 111, 123]
	NO_x	approx. 55–80% reduction	Lower combustion temperature, oxygenated molecule	A slightly lower flame temperature may affect performance	
	PM	approx. 95–99% reduction	Clean, oxygenated combustion	—	
	Unregulated aldehydes	Increase (Formaldehyde dominant)	Partial oxidation intermediates (HCHO, HCOOH)	Local air toxicity, health risk	[26, 102, 169, 171, 172]
LNG (TtW)	SO_x	approx. 100% reduction	No sulfur content	—	[2, 10, 62, 92, 100, 116]
	NO_x	approx. 80–90% reduction	Lean premixed combustion	Engine-type dependent	
	PM	approx. 100% reduction	No heavy hydrocarbons	—	
LNG (WtW)	CO_2e	approx. 15–23% reduction (HPDF engines)	High efficiency, lower carbon ratio	Methane slip (up to 1–2%)	[3, 12, 61, 69, 70, 85-88, 95, 124, 139, 142, 143, 154, 176, 181]
Methanol (WtW)	CO_2e	Grey/Brown: more than Diesel (increase)	Fossil feedstock (coal/natural gas)	High upstream CO_2	[56, 93, 126, 140, 180]
	CO_2e	Blue: Moderate reduction	Fossil methanol + CO_2 capture	Capture efficiency critical	[7, 120, 166]
	CO_2e	Green: approx. 50–70% reduction	Renewable H_2 + CO_2 captured from air/biogenic	Cost and scalability	
e-/bio-LNG	CO_2e	Potential Moderate reduction, but less than "green" methanol	Renewable methane synthesis	High cost, low efficiency	[29, 37, 46, 55, 76]

5.4. Limitations and uncertainty

Despite extensive literature coverage and methodological harmonization, several limitations and uncertainties should be acknowledged when interpreting the comparative findings of methanol and LNG as alternative marine fuels.

First, LCA heterogeneity remains a key challenge. Published WtW studies differ substantially in their system boundaries, allocation methods, and upstream process emission factors. Some include full supply-chain emissions from extraction to combustion, whereas others limit the scope to WtT or TtW phases. These methodological inconsistencies introduce uncertainty of up to ±20–30% in the reported WtW GHG reduction potential.

Second, methane slip variability significantly affects the real-world climate performance of LNG-fueled engines. Reported slip rates range from below 0.2% for HPDF engines to over 3% for LPDF engines, depending on engine type, operating load, and maintenance conditions. Even small deviations in slip rates can negate much of LNG's nominal CO_2 advantage over diesel on a GWP_{100} basis, particularly under low-load or maneuvering operation.

Third, there is considerable uncertainty surrounding the scalability and supply chain maturity of green methanol. Current global production capacity for electro- and bio-methanol is limited, and its cost remains several times higher than that of fossil methanol or LNG. The climate benefits of green methanol are strongly dependent on the carbon intensity of the hydrogen source and the capture efficiency of the CO_2 feedstock. Supply-chain emissions associated with renewable electricity generation and CO_2 transport also introduce variability across case studies.

Finally, data transparency and measurement gaps, particularly the lack of consistent onboard monitoring of methane emissions and aldehyde formation, limit the ability to validate modeled or laboratory results under operational conditions. In addition, the dynamic regulatory landscape (e.g., updates to IMO GHG strategy and FuelEU Maritime) adds uncertainty to long-term economic projections and compliance costs.

Future research should prioritize:

1. Standardized WtW methodologies for marine fuels that harmonize functional units, GWP metrics, and boundary definitions.
2. Continuous onboard monitoring of methane slip and unregulated emissions to build real-world datasets for model validation.
3. Techno-economic optimization studies evaluating the integration of carbon capture and renewable hydrogen for scalable green methanol pathways.
4. Cross-sectoral LCA databases with transparent data sharing to reduce duplication and improve comparability across studies.

Together, these actions would enhance the robustness of future assessments and support evidence-based decision-making in the maritime decarbonization transition.

6. Infrastructure, storage, and safety

6.1. Onboard storage and space requirements

Methanol has a volumetric energy density of approx. 15.7 MJ/L versus approx. 36.6 MJ/L for MDO. Therefore, on an equal-energy basis, methanol requires roughly 2.2–2.5 times of the tank volume of MDO to achieve the same range [65, 66, 104]. Because methanol is a liquid at ambient temperature and pressure, it can be stored in simple, non-pressurized tanks and handled with conventional liquid-fuel systems (with material compatibility and gas detection precautions), and several retrofit studies and pilot projects have demonstrated that existing ballast tanks can be repurposed as methanol fuel tanks (subject to coatings, cofferdams and safety segregation) when performing a conversion [36, 66, 123].

LNG fuel storage generally requires significantly more volume than MDO to achieve the same operational range.

The difference arises primarily from LNG's lower volumetric energy density (approx. 22 MJ/L) compared with MDO (approx. 36.6 MJ/L). Peer-reviewed analyses indicated that the net LNG fuel volume required to supply equivalent energy is typically about 1.6–2.0 times that of MDO [63, 122, 135]. However, when system-level factors, such as cryogenic insulation, structural supports, and safety spacing, are considered, the effective installed volume of LNG tanks can reach 2.5–4.0 times that of MDO tanks. This higher space requirement results from the need for specialized, highly insulated cylindrical or spherical Type C containment systems that minimize boil-off and maintain cryogenic conditions [122]. Consequently, LNG fuel storage imposes additional design constraints on ship layout, increases overall weight, and can reduce available cargo capacity, particularly for retrofit installations or small vessels [63, 135]. In summary, while the intrinsic physical energy properties of LNG dictate roughly double the fuel volume requirement, practical marine engineering considerations amplify this to an overall onboard space penalty of approx. 3-4 times that of MDO.

6.2. Bunkering Infrastructure

Methanol bunkering is operationally simpler and less capital-intensive than LNG bunkering. As a liquid at ambient temperature and pressure, methanol can be handled, stored, and transported using conventional chemical-industry infrastructure, allowing existing tankage and pipelines to be adapted with minor modifications [81, 123, 168]. Bunkering can be performed via truck-to-ship (TtS) or ship-to-ship (StS) operations without cryogenic or high-pressure systems, leading to shorter transfer times, typically reported as up to 50% faster than LNG operations in industry practice [66, 123]. Comparative techno-economic analyses confirmed that methanol infrastructure investment and handling costs are significantly lower than those for LNG, largely due to the absence of specialized insulation, vapor recovery systems, and safety clearances required for cryogenic fuels [123, 179]. Furthermore, methanol distribution benefits from mature global supply chains, with storage facilities already available at over 100–125 major ports worldwide according to the Methanol Institute, a figure reported and cited in peer-reviewed assessments of port readiness [81, 168]. This extensive infrastructure base, combined with simplified logistics and lower capital costs, underpins methanol's growing attractiveness as a near-term marine fuel alternative to LNG.

Unlike methanol, LNG bunkering is a complex and capital-intensive process due to its cryogenic nature and the stringent safety requirements involved. LNG must be stored at approx. −162°C, necessitating double-walled, vacuum-insulated storage systems and specialized transfer pipelines [20, 177]. The bunkering process involves multiple safety zones, inert gas purging, and boil-off gas management, all of which contribute to longer bunkering times and higher operational costs compared to conventional liquid fuels [15, 20]. Typical LNG bunkering operations take roughly twice as long as those for methanol or MDO and require extensive crew training and emergency procedures to mitigate cryogenic and flammability hazards [177]. Infrastructure availability also remains limited. As of 2024, LNG bunkering is supported at approx. 200 ports worldwide, far fewer than the more than 125 ports capable of handling methanol [15, 177]. Consequently, while LNG provides substantial emission benefits, its high infrastructure cost, operational complexity, and logistical constraints hinder rapid deployment compared to methanol, which leverages existing liquid fuel handling systems and port facilities.

In conclusion, methanol and LNG differ substantially in terms of bunkering logistics, infrastructure requirements, and operational complexity. Methanol, being a liquid at ambient temperature and pressure, can be handled using conventional fuel storage and transfer systems, allowing for easy integration into existing port infrastructure. Methanol bunkering is considered to be relatively simple, less expensive, and can typically be completed in about half the time required for LNG refueling. Moreover, methanol benefits from a well-established global logistics network, with storage and handling facilities already available at more than 125 of the world's largest ports. Its compatibility with existing liquid-fuel supply chains allows for retrofitting of conventional bunkering terminals with minimal modifications.

In contrast, LNG bunkering presents more stringent technical and safety challenges. LNG must be stored at cryogenic conditions of approx. −162°C, requiring double-walled, vacuum-insulated tanks and specialized transfer systems equipped with boil-off gas management and inert gas purging. These design and operational constraints significantly increase both the capital cost and complexity of LNG bunkering operations. Typical LNG refueling takes roughly twice as long as that for methanol or MDO and demands strict adherence to safety protocols and crew training standards. Although LNG bunkering infrastructure has expanded rapidly, reaching roughly 200 ports worldwide by 2024, it still lags behind methanol in terms of global availability and logistical flexibility. Consequently, while LNG provides substantial emission reduction potential, its deployment is limited by the higher cost, operational complexity, and infrastructure demands associated with cryogenic fuel systems, whereas methanol's ambient liquid state and compatibility with existing infrastructure position it as a more practical near-term solution for low-carbon marine fuels.

6.3. Safety and handling

The safety profiles of methanol and LNG are fundamentally different and require distinct mitigation strategies. Methanol's hazards are primarily static, stemming from its inherent chemical properties. It is highly toxic through ingestion, inhalation, or skin absorption, exposure to as little as 30 mL can cause blindness or death, and its low flash point of approx. 12°C makes it easily flammable with an almost invisible flame under sunlight, posing significant fire risks during handling and operation [1, 68, 123]. Consequently, methanol safety management emphasizes containment integrity, double-walled fuel systems, continuous gas detection, and specialized crew training [68, 123].

In contrast, LNG's hazards are dynamic, associated with its cryogenic physical state and the risks arising from phase change. In its liquid form, LNG is neither flammable nor explosive; however, when vaporized, methane–air mixtures within 5–15% concentration become flammable and can form large vapor clouds capable of ignition or explosion [24, 57]. Additionally, contact with cryogenic LNG can cause severe cold burns and structural embrittlement, while the rapid vaporization of a small spill may displace oxygen, leading to asphyxiation hazards. Therefore, LNG risk mitigation primarily focuses on preventing and controlling vapor releases, maintaining cryogenic containment integrity, and ensuring safe venting and insulation practices [24, 57, 119].

7. Economic viability and total cost of ownership

7.1. Capital and operating costs

The capital cost implications of adopting alternative marine fuels vary considerably between methanol and LNG. Industry and peer-reviewed studies consistently indicate that LNG-fueled new buildings require substantially higher capital expenditure (CAPEX) than conventional MDO designs, typically approx. 22–40% higher, due to the need for cryogenic tanks, double-wall piping, and complex fuel-gas handling systems. In contrast, methanol-fueled newbuilds show smaller CAPEX premiums, commonly in the range of 10–25%, because methanol can be stored at ambient temperature and pressure using simpler fuel-delivery equipment [19, 144].

For existing tonnage, retrofit costs for methanol engines are estimated at roughly €250–€650 per kW, encompassing engine conversion, fuel-supply system, and safety upgrades, with lower values expected for subsequent retrofits as experience grows [67, 174]. Comparable LNG retrofits generally demand higher investment because of cryogenic storage and gas-handling complexity. Collectively, these data illustrate that methanol offers a less capital-intensive pathway to compliance and early decarbonization than LNG, albeit with smaller immediate GHG benefits.

7.2. Fuel costs and regulatory impact

Economic and techno-environmental analyses indicate that the total cost of ownership (TCO) and lifetime fuel costs of LNG and methanol pathways depend strongly on engine technology, regulatory context, and fuel price assumptions. Peer-reviewed LCAs and cost studies show that while both fuels entail higher capital expenditure than conventional designs, their operational and compliance costs vary substantially across scenarios [54, 75, 93, 174, 179]. Kanchiralla et al. [75] and Gore et al. [54] demonstrated that the economic competitiveness of LNG and methanol is highly sensitive to carbon pricing and upstream energy intensity. Similarly, Lee et al. [93] and Zamboni et al. [179] reported that methanol's viability improves markedly under decarbonization policies such as FuelEU Maritime, while LNG remains favorable in low-carbon-price contexts due to lower near-term compliance costs. Wu et al. [174] performed a full TCO analysis and concluded that methanol DF vessels exhibit only a modest cost premium compared with conventional diesel ships when lifetime operating costs and potential carbon charges are included. Industry analyses corroborate these findings: the SEA-LNG consortium reported that the lifetime fuel cost of the LNG pathway can be approx. half that of methanol when regulatory compliance costs are considered [42], reflecting the fact that grey LNG already meets short- to mid-term GHG compliance thresholds, whereas grey methanol requires immediate blending with costly green fuels. Conversely, a DNV commercial case study found that the TCO for a methanol-fueled 5,500 TEU container vessel was only 0.4% higher than a conventional counterpart over a 25-year life cycle, emphasizing that the increased fuel-flexibility capability comes at little to no extra cost [41]. Overall, these results suggest that the modest CAPEX premium for methanol-capable designs represents a strategic investment in long-term fuel optionality, while LNG offers short-term economic advantages under current compliance regimes. The comparative economic indicators for Methanol and LNG as marine fuels are presented in Table 7.

Table 7. Comparative economic indicators for methanol and LNG as marine fuels

Parameter	Methanol	LNG	References
Newbuilding CAPEX	Increase 10% over conventional diesel vessels (typical range: increase 8–12%) due to minor engine and tank modifications.	Increase 22% over conventional diesel vessels (typical range: increase 20–25%) due to cryogenic storage systems, double-walled piping, and safety equipment.	[41, 75, 174, 179]
Retrofit Cost	Estimated €250–650 per kW depending on engine type and tank design. Retrofit usually involves add-on components (fuel system, tanks, control upgrades).	Requires near complete overhaul of fuel system and engine; cost can exceed €800–1,200 per kW.	[41, 174, 179]
Fuel Price (2024 average)	Fossil methanol approx. $500–650 / t; "green" methanol approx. $1,200–1,800 / t (price volatility high; limited supply).	Fossil LNG approx. $350–450 / t; Bio-LNG/e-LNG approx. $1,000–1,500 / t.	[42, 54, 75, 93]
Cost of Compliance (FuelEU Maritime, 2025–2040)	Requires immediate blending with "green" methanol to meet GHG targets; high short-term compliance cost but low long-term penalty once green supply scales.	Fossil LNG provides sufficient GHG reduction for compliance until approx. 2040 under FuelEU Maritime; blending not required initially.	[41, 42, 93]
Total Cost of Ownership (TCO)	approx. +0.4% higher than diesel over 25 years; flexible transition pathway to "green" methanol.	Lifetime fuel cost approx. 50% lower than methanol pathway due to lower compliance costs and established infrastructure.	[41, 42, 174]
Strategic Outlook	"Future-proof" long-term decarbonization option with seamless transition to "green" methanol.	"Bridge fuel" offering immediate compliance and cost advantages but challenged by methane slip and long-term GHG limits.	[41, 42, 54, 75, 93, 174, 179]

8. Real-world applications and market outlook

8.1. Case studies and pilot projects

Methanol adoption in shipping has accelerated in recent years, driven by both commercial orders and demonstration projects that signal market confidence in the fuel pathway. Recent review and comparative studies document growing interest in methanol as a near-term low-carbon fuel and summarize the expanding project pipeline [123, 179]. A.P. Moller-Maersk's strategic decision to order multiple methanol-capable vessels in mid-2023 represents a major market signal, demonstrating that leading container operators view methanol as a credible primary decarbonization route [113]. Real-world demonstrations further underline progress: the Port of Antwerp–Bruges-supported "Methatug" project delivered the world's first methanol-powered tug, and industry announcements describe the retrofit of the containership Maersk Halifax to DF methanol operation, both milestones that illustrate technical and operational feasibility at different vessel scales [11, 112, 147]. By contrast, LNG has a much longer maritime history (the first seaborne LNG operations date to the Methane Pioneer era in the late 1950s) and today there are substantially more LNG DF vessels in service and on order than methanol ships; industry fleet databases and independent analyses report hundreds of LNG-fueled vessels and a continuing orderbook, with major operators such as CMA CGM committing to large-scale LNG deployment alongside other fuel strategies [20, 25, 43, 98, 145]. The major milestones in the adoption of Methanol and LNG as marine fuels are presented in Table 8.

8.2. Strategic outlook

LNG's longer history in commercial shipping has produced a clear first-mover advantage, an established installed base of DF vessels, bunkering infrastructure and supply chains, which generates positive feedbacks that lower unit costs and further entrench LNG as a pragmatic near-term option [47, 140]. However, recent strategic commitments by major shipowners, most notably A.P. Møller-Maersk's large methanol orders and upstream supply agreements, signal a competing industry vision that prioritizes a fuel pathway with a clearer long-term route to deep decarbonization, even if that choice requires a more active role in developing green supply chains and policy frameworks [123, 138]. The academic literature frames this divergence as two legitimate strategic approaches to the maritime energy transition: an incremental/bridge strategy (LNG) that reduces near-term emissions and leverages existing infrastructure, and a transformational strategy (methanol/e-methanol/bio-methanol) that seeks long-term carbon neutrality but depends on the emergence of scalable green feedstocks and supportive regulation [93, 138, 179]. Empirical studies and techno-economic modelling demonstrate that the economic attractiveness of each path is highly scenario-dependent, sensitive to carbon pricing, methane-slip performance, and the pace and cost of green fuel deployment, so fleet decisions increasingly reflect corporate risk profiles and regulatory expectations as much as current fuel price differentials [93, 179].

9. Conclusions and strategic recommendations

9.1. Conclusions

This review provides a structured, PRISMA-based comparative synthesis of methanol and LNG as alternative fuels for marine diesel engines, integrating engine thermodynamics, TtW emissions, WtW LCAs, infrastructure constraints, safety considerations, and techno-economic performance into a unified decision-oriented framework.

Key scientific contributions of this review

1. Integrated multi-dimensional comparison

Unlike prior fuel-specific reviews, this study consolidates performance, lifecycle emissions, safety, infrastructure, and cost data into a single comparative structure, enabling cross-domain evaluation rather than parallel narrative discussion.

Table 8. Major milestones in the adoption of Methanol and LNG as marine fuels

Year	Fuel	Milestone/Project	Description and Significance	References
1959	LNG	Methane Pioneer voyage	First-ever seaborne LNG cargo; marked the start of LNG marine transportation and development of cryogenic fuel systems.	[20]
2014–2019	LNG	Early commercial DF vessels	Widespread adoption of LNG DF engines (MAN ME-GI, Wärtsilä DF) for ferries, container ships, and tankers; proven operational safety and reliability.	[20, 145]
2022	LNG	CMA CGM fleet expansion	CMA CGM confirms large-scale LNG strategy, planning > 150 DF vessels by 2029, combining LNG and biomethane options.	[25, 98]
2023	Methanol	Maersk methanol vessel order	Maersk orders six methanol-powered container ships—first global top-tier liner commitment to methanol as a decarbonization pathway.	[113]
2024	Methanol	Methatug project (Port of Antwerp–Bruges)	Delivery of the world's first methanol-fueled tugboat, a milestone for port operations and small-vessel decarbonization.	[11]
2024	Methanol	Maersk Halifax retrofit	World's first large container ship converted to DF methanol operation, proving retrofit feasibility at commercial scale.	[112, 147]
2025	LNG	Record LNG-fueled orderbook	DNV reports "unprecedented year" for LNG-fueled ship orders; LNG remains dominant among alternative-fuel designs.	[43, 145]

2. Technology-dependent climate differentiation

The analysis demonstrates that LNG's climate benefit is not fuel-intrinsic but engine-configuration-dependent. HPDF engines can achieve approx. 15–23% WtW GHG reduction, whereas low-pressure systems may negate this advantage due to methane slip variability (0.2–3%). Thus, LNG's decarbonization effectiveness is conditional rather than universal.

3. Pathway-dependent methanol performance

Fossil ("grey") methanol does not offer WtW climate advantages over diesel, while "green" methanol can reduce WtW emissions by approx. 50–70%, making feedstock origin the decisive factor in its long-term viability.

4. Strategic trade-off clarification

The LNG–methanol choice is fundamentally a trade-off between:

- Immediate regulatory compliance with moderate GHG reduction (LNG), and
- Long-term carbon neutrality potential with supply-chain uncertainty (green methanol).

Decision-oriented strategic synthesis

Based on the integrated findings:

- For short-term (2025–2040) compliance under FuelEU Maritime or IMO CII frameworks, LNG – particularly in HPDF configuration – offers lower compliance risk and stronger near-term economic competitiveness.
- For long-term net-zero alignment (post-2040 scenarios), methanol provides a clearer decarbonization trajectory due to its compatibility with scalable renewable hydrogen pathways.
- For retrofit feasibility and infrastructure simplicity, methanol presents lower CAPEX premiums (≈10–25% vs 22–40% for LNG newbuilds) and reduced bunkering complexity.
- For vessels sensitive to cargo-space penalties, LNG imposes higher volumetric installation penalties (up to 3–4× effective tank volume vs MDO when system factors are included).

Overall strategic conclusion

LNG should be regarded as a bridge fuel whose climate credibility depends on methane-slip control, while methanol should be considered a platform fuel whose ultimate success depends on green production scale-up.

Therefore, the optimal fuel pathway is not universal but scenario-dependent, shaped by:

- Carbon pricing trajectories
- Methane regulation intensity
- Renewable hydrogen deployment speed
- Vessel lifetime and retrofit horizon.

Future research must prioritize standardized WtW methodologies, real-world methane monitoring, and techno-economic optimization of green methanol production to reduce decision uncertainty.

Table 9 synthesizes the integrative strategic comparison between methanol and LNG under different regulatory and technological scenarios.

Table 9. Decision-oriented strategic comparison of Methanol and LNG as marine fuels

Decision dimension	Methanol pathway	LNG pathway	Strategic implication
Near-Term Regulatory Compliance (2025–2040)	Requires blending with green methanol to meet stringent GHG targets	HPDF LNG provides immediate approx. 15–23% WtW GHG reduction	LNG favored for short-term compliance under moderate carbon pricing
Long-Term Net-Zero Alignment (Post-2040)	Green methanol enables approx. 50–70% WtW reduction; scalable with renewable H_2	Fossil LNG limited by methane slip; e-/bio-LNG less scalable	Methanol favored for long-term deep decarbonization
Engine Technology Maturity	Retrofit-friendly; incremental modification of CI engines	HPDF mature; LPDF sensitive to methane slip	Both technically viable; LNG performance more configuration-dependent
Methane / Aldehyde Risk	Formaldehyde formation (local toxicity concern)	Methane slip (high GWP climate concern)	LNG risk more critical for global climate metrics
Onboard Space Requirement	approx. 2.2–2.5× MDO tank volume	Effective 3–4× MDO volume (system-level)	Methanol more favorable for space-constrained retrofits
Infrastructure Complexity	Compatible with existing liquid-fuel logistics	Requires cryogenic bunkering and safety zones	Methanol easier for rapid infrastructure scaling
Capital Expenditure (Newbuild)	approx. +10–25% vs diesel	approx. +22–40% vs diesel	Methanol lower upfront premium
Strategic Role	Platform fuel for green transition	Transitional bridge fuel	Choice depends on corporate risk horizon

9.2. Strategic recommendations

- Shipowners: Adopt methanol-ready or DF designs to ensure compliance flexibility under progressively stringent carbon-intensity and fuel life-cycle regulations (e.g., IMO CII, FuelEU Maritime)
- Engine manufacturers: Prioritize R&D on methanol combustion optimization and high-pressure LNG systems that minimize methane slip and maximize thermal efficiency
- Policy-makers: Implement targeted incentives for renewable methanol and bio-LNG infrastructure, including carbon credits, green corridor support, and certification frameworks to accelerate scale-up
- Researchers: Harmonize WtW LCA methodologies and expand real-world measurement campaigns on unregulated aldehyde emissions (methanol) and methane slip (LNG)
- Port authorities and regulators: Establish a coordinated international framework to standardize methanol bunkering safety protocols and mandate transparent monitoring and reporting of methane slip from LNG-fueled vessels. These measures will ensure safe fuel handling, enhance inter-port data consistency, and underpin glob-

ally harmonized compliance systems aligned with the IMO's 2023 GHG Strategy.

Collectively, these actions will enable a balanced transition – leveraging LNG's readiness for near-term compliance while building the foundation for a methanol-based, carbon-neutral maritime sector in the coming decades.

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Nomenclature

bio-LNG	biomethane
BSFC	brake-specific fuel consumption
BTDC	before top dead center
BTE	brake thermal êfficiency
CA	crank angle
CAPEX	capital expenditure
CH_3OH	methanol
CH_4	methane
CIEs	compression-ignition engines
CII	carbon intensity indicator
CO	carbon monoxide
CO_2	carbon dioxide
CR	compression ratio
DF	dual-fuel
DI	direct-injection
EC	European Commission
e-LNG	synthetic methane
ETS	emissions trading system
EU	European Union
GHG	greenhouse gas
GWP	global warming potential
HFO	heavy fuel oil
HPDI	high-pressure direct injection
ICCT	International Council on Clean Transportation
IMO	International Maritime Organization
LCAs	life-cycle assessments
LNG	liquefied natural gas
MDO	marine diesel oil
MN	methane number
NO_x	nitrogen oxides
PM	particulate matter
R&D	research and development
SOx	sulfur oxides
StS	ship-to-ship
TCO	total cost of ownership
TDC	top dead center
TtS	truck-to-ship
TtW	tank-to-wake
uHC	unburnt hydrocarbon
VLSFO	very-low-sulfur fuel oil
WtW	well-to-wake

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