Two-stroke low-speed engines and maritime transition to net-zero

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Abstract: *The world's maritime industry is currently undergoing an unprecedented transformation, driven by the climate crisis and the strict regulations imposed by the International Maritime Organization (IMO). The IMO's Greenhouse Gas (GHG) Strategy for 2023 has fundamentally redefined the industry's goals, from gradually reducing carbon intensity to comprehensively phasing out greenhouse gas emissions by 2050. At the heart of this transition is the low-speed, two-stroke engine, which serves as the main source of propulsion for most deep-sea merchant ships. Contrary to being considered a legacy of the limitations of the fossil fuel-dependent era, these engines are being transformed into highly efficient and adaptable platforms capable of using the next generation of carbon-neutral and zero-carbon energy carriers. This analysis examines the technical, operational and regulatory mechanisms that enable the maritime sector to meet its net-zero emission commitments, with a particular focus on dual-fuel engine architectures, advanced combustion control, and the holistic integration of ship energy systems.*

Keywords: *TWO-STROKE LOW-SPEED ENGINES, NET-ZERO 2050, ALTERNATIVE MARINE FUELS, EMISSION REDUCTION*

1. Introduction

Two-stroke slow-speed diesel engines are used in majority on big containers ships. The two-stroke low-speed engine prevails in maritime applications because of its endurance and high thermal efficiency, generally exceeding 50%. Low-speed engines have an extended combustion stroke, enabling the complete burning of complex fuels. This feature makes the two-stroke engine a strong option for using alternative fuels.

The adoption of the 2023 IMO GHG Strategy represents a historic deal in the fight against climate change and signifies a breakthrough in reducing the environmental impact of international shipping. This revised strategy replaces the 2018 initial target of a 50% reduction in emissions by 2050 with a much more ambitious goal of reaching well-to-wake (WTW) net-zero emissions. The WTW perspective is critical, as it accounts for emissions throughout the entire fuel lifecycle, from production and transport to combustion at sea, thereby preventing the mere shifting of emissions to other industrial sectors [1].

To provide the industry with a clear trajectory, the IMO established a series of ambition levels and indicative checkpoints for 2030 and 2040. These milestones are designed to ensure that the global fleet stays on track with the Paris Agreement's 1.5°C temperature goal [2].

Table 1: *IMO Decarbonization Targets (Base Year 2008).*

Milestone Year	Minimum Ambition Level	Strive Target (1.5°C Aligned)	Primary Regulatory Mechanism
2030	20% Absolute GHG Reduction	30% Absolute GHG Reduction	CII Rating / EEXI Compliance
	40% Carbon Intensity Reduction	—	Fuel GHG Intensity Standard
	5% ZNZ Fuel Uptake	10% ZNZ Fuel Uptake	Early Market Incentives
2040	70% Absolute GHG Reduction	80% Absolute GHG Reduction	Global Fuel Standard / Pricing
2050	Net-Zero GHG Emissions	—	Net-Zero Framework (NZF)

The IMO's Net-Zero Framework (NZF) is the regulatory response to these goals [3]. The NZF sets a goal-based marine fuel standard that controls the gradual decrease of GHG intensity. It also includes an economic aspect: the first-ever global maritime GHG emissions pricing mechanism. Starting in 2028, this mechanism is expected to set an initial price of about USD 100 per ton, which would bring in between USD 11 billion and USD 13 billion a year. These funds will help pay for the development of zero- and near-zero (ZNZ) fuels, which will help close the big price gap between regular heavy fuel oil (HFO) and alternative fuels, which are usually three to four times pricier. The NZF only applies to ships that are more than 5,000 gross tons and travel across oceans. These ships are responsible for 85% of all emissions.

The framework's adoption was pushed back by a year in late 2025, but the need to cut carbon emissions is still strong. The move is a clear sign to shipowners that the time of using fossil fuels is coming to an end.

Classic regulations often looked only at tank-to-wake (TTW) emissions, or what comes out of the exhaust, so, e.g., "green" gases or e-fuels seemed perfect. When you turn on WTT, you see that some fuels have very low TTW emissions (e.g., hydrogen, ammonia) but can have high WTT emissions if produced from fossil sources without capturing CO_2 . Conversely, some fuel may have moderately high TTW emissions but a very favorable WTT if, for example, it is an advanced biofuel from waste.

To meet plans of net zero using two-stroke slow-speed engines alternative fuels like hydrogen, methanol and ammonia have to be used (Fig. 1). The MAN B&W ME series and WinGD X-engines exhibit a trend towards electronic regulation. Electronically controlled engines can accurately regulate fuel injection timing and pressure to accommodate the diverse physical and chemical properties of alternative fuels. Marine two-stroke engines have a high volume-to-surface ratio. This reduces heat loss through the walls and makes the temperature in the combustion chamber more even. This feature is especially useful when burning fuels like ammonia and methanol. Also, the dual-fuel design lets these engines run on regular fuels until the bunkering infrastructure for alternative fuels is ready.

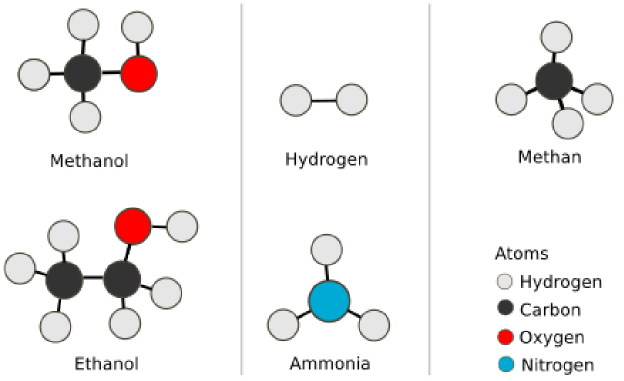

Fig. 1 *Fuels that are in consideration for use in future to meet net-zero or near neto-zero emissions in maritime.*

2. Analysis of alternative fuels and other measures

Methanol and Ethanol

Methanol has become a leading and economically viable option for reducing carbon emissions in shipping. This is due to its liquid state at room temperature and the technological advancements that have been made.

Two-stroke methanol engines, such as the MAN B&W ME-LGIM, have been in operation since 2016, primarily on methanol carriers [5]. Recently, this technology has expanded into the Very Large Container Vessel (VLCV) segment, with hundreds of orders placed by major carriers.

When produced as green methanol using renewable hydrogen and captured CO_2, this fuel has almost no emissions throughout its life cycle. From a tank-to-wake perspective, burning methanol significantly reduces emissions and almost eliminates particulate matter. The diesel-cycle methanol engine utilizes a high-pressure direct injection system, where a small amount of pilot fuel is used to initiate combustion, maintaining the high efficiency associated with the conventional diesel process.

Ethanol is gaining traction as a secondary alcohol fuel, particularly in regions where bioethanol is produced competitively from agricultural biomass [6]. WinGD has pioneered the development of the first ethanol-fueled two-stroke engine, with deliveries scheduled to begin in 2026 [6]. This engine is an adaptation of the X-DF-M methanol platform, utilizing the same combustion concept and safety regulations [7].

Ethanol's technical challenges include its higher energy density compared to methanol. This requires changes to the fuel injector nozzle design and control systems to optimize the injection volume [6]. Research starting in 2014, like the EU-funded HERCULES 2 project, has confirmed the use of flexible injectors for different alcohol fuels, giving shipowners more options for fuel [6].

Ammonia

Ammonia is fuel that does not have carbon atoms so when burning it does not generate CO_2 emissions, but it does generate NO_x emissions and postprocessing is necessary to annulate them.

Ammonia (NH_3) is widely regarded as a critical enabler for the 2050 net-zero target because it contains no carbon and can be produced at scale as green ammonia using renewable energy [8]. However, its slow burning velocity, high auto-ignition temperature, and toxicity present formidable engineering hurdles.[4]

Major engine designers have achieved significant milestones in ammonia propulsion. MAN Energy Solutions completed full-scale testing of its two-stroke ammonia dual-fuel engine in Copenhagen in late 2024 [4]. Similarly, WinGD delivered its first X-DF-A ammonia-fueled engine for installation on an EXMAR LPG carrier in 2025 [7] In Japan, the Green Innovation Fund project has supported the construction of the MAN B&W 7S60ME-Ammonia engine by Mitsui E&S, which will power a Newcastlemax bulk carrier built by Imabari Shipbuilding [9].

Ammonia combustion in two-stroke engines typically utilizes a diesel-cycle combustion process with a 5% mass (or energy) of diesel pilot fuel [8]. This approach addresses ammonia's poor ignition properties and allows for controlled combustion timing. A major concern with ammonia is the production of nitrous oxide, a greenhouse gas that is 298 times more effective at trapping heat than CO_2 [10]. Research indicates that advancing the pilot fuel injection timing (e.g., to 30° BTDC) can significantly reduce NO_x and unburned ammonia emissions. [11]

Advanced Combustion Control and Aftertreatment Systems

To comply with the IMO's Tier III limits while operating on alternative fuels, two-stroke engines rely on a combination of sophisticated in-cylinder measures and external exhaust aftertreatment.

Modern combustion control strategies involve the use of Variable Compression Ratio (VCR) and electronic injection timing to adapt to different fuel reactivities [12]. For ammonia engines, multi-pulse or split injection of pilot fuel has been shown to improve mixture preparation and reduce pressure oscillations [11]. Injector orientation and nozzle spray angles are also being optimized; vertical orientations with symmetric spray angles can reduce formation by up to 85% compared to conventional diesel combustion [13].

Selective Catalytic Reduction (SCR) remains the primary technology for abatement. In ammonia engines, SCR systems are particularly vital as they can also neutralize any ammonia slip that escapes the combustion chamber [14]. For LNG engines, the introduction of Intelligent Control by Exhaust Recirculation (iCER) has proven effective in reducing methane slip by 50% while improving thermodynamic efficiency [12].

Integrated, on-engine aftertreatment solutions are becoming the industry standard, allowing for more compact engine room designs and lower installation costs. These systems ensure that vessels remain compliant with air quality regulations while pursuing global GHG targets.

Integration and Hybridization

Decarbonization cannot be achieved by engine technology alone; it requires the optimization of the entire ship's energy system. As alternative fuels are more expensive and possess lower energy densities, the "efficiency first" is very important principle.

The integration of battery energy storage systems (BESS) with the main two-stroke engine allows for peak shaving and optimized spinning reserves [12]. By utilizing shaft generators—also known as Power Take-Off (PTO) systems—vessels can generate electrical power from the efficient main engine, reducing the need to operate less efficient auxiliary diesel generators.

Hybrid control systems, exemplified by WinGD's X-EL, regulate energy distribution among the main engine, shaft generator, and batteries, thereby maintaining the main engine's optimal operational efficiency. This strategy can diminish overall fuel consumption by 0.1–0.5 tons daily, translating to potential annual savings of up to USD 320,000 per vessel, contingent upon fuel type and operational parameters [15].

Furthermore, waste heat recovery systems, which harness thermal energy from exhaust gases to power steam turbines or supply process heat, are becoming increasingly vital on vessels utilizing cryogenic or ammonia-based fuels.

Hybrid arrangements incorporating fuel cells and batteries have shown promise in reducing emissions associated with shipboard power generation [16].

Operational Efficiency: EEXI, CII, and the Role of Slow Steaming

Operational measures provide the most immediate pathway to emission reductions, often requiring minimal capital expenditure compared to technical retrofits [17]. The regulatory drivers for these measures are the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII).

A ship's speed and its fuel consumption are related in a way that isn't straightforward. Reducing speed, often called "slow steaming," can significantly lower fuel use and is often the main method ships use to improve their CII ratings [17]. Moreover, digital tools, such as data-driven voyage planning and weather routing, help improve operational efficiency.

Calculations suggest that if shipowners only focus on changing fuels without improving efficiency, the industry won't meet the 2030 indicative checkpoint [1]. This highlights the importance of these measures.

***Table 2:** Effectiveness of Short-Term Operational and Technical Efficiency Measures*

Strategy	Estimated GHG Reduction Potential	Implementation Difficulty	Regulatory Context
Vessel Size Optimization	47%	High (Fleet Planning)	EEDI / EEXI
Speed Reduction / Slow Steaming	20–30%	Low (Operational)	CII Compliance
Hull Shape Optimization	15%	Moderate (Newbuild)	EEDI Phase 3
Air Lubrication Systems	8%	Moderate (Retrofit)	CII Improvement
Advanced Hull Coatings	5%	Low (Maintenance)	SEEMP Part III

Future Scenarios to 2050: Biofuels, Nuclear, and Arctic Routes

As the industry approaches 2050, several distinct pathways emerge depending on fuel availability and technological breakthroughs.

Sustainable biofuels, such as Hydrotreated Vegetable Oil (HVO) and Fatty Acid Methyl Esters (FAME), offer a "drop-in" solution that is fully compatible with existing two-stroke engines. While biofuels are crucial for achieving immediate objectives, their sustained utility may be constrained by the availability of feedstocks and competition from the aviation and terrestrial transportation industries.

For sectors where zero-carbon fuels are not feasible because of energy density constraints, like Ultra-Large Container Vessels (ULCVs) operating on high-speed routes, nuclear propulsion is being re-evaluated as a potentially disruptive technology [18]. Contemporary Small Modular Reactors (SMRs) present a high-power density and a 20-year operational lifespan, which could eliminate all bunker expenses and carbon-related costs. Lloyd's Register's analysis suggests that a 15,000 TEU nuclear-powered containership could attain a 38% greater annual cargo capacity by maintaining a speed of 25 knots, in contrast to slow-steaming vessels [19].

The opening of the Arctic Sea Route due to polar ice melt offers the potential to reduce voyage distances between Europe and Asia by 40%. While this could reduce emissions per voyage, modeling suggests that increased total traffic and the lack of strict fuel standards in the region could raise global shipping emissions by 8.2% by 2100 unless a net-zero strategy is strictly enforced in Arctic waters [20].

Economics of the Global Fuel Transition

A global carbon pricing system is crucial for encouraging the transition from fossil fuels. Without such a system, the higher cost of green methanol or ammonia is often a barrier for many operators. The International Maritime Organization's proposed price of USD 100 per ton of CO2 is a starting point, but researchers suggest that higher prices may be needed to meet the 1.5°C limit [21]. Investing in energy efficiency on ships can significantly reduce the overall cost of this transition. Each percentage point of increased efficiency lowers the total need for expensive alternative fuels, which in turn reduces the investment needed for green fuel production infrastructure [1].

3. Conclusion

The maritime industry is no longer at a crossroads; it has chosen the path of decarbonization. The continued innovation in two-stroke propulsion and shipboard energy management ensures that this journey toward net-zero is not only technically feasible but also commercially sustainable for the global fleet.

To meet the needs of the world's clean energy fleet, currently unavailable amounts of renewable solar and wind energy are needed. Not only ships compete for this energy, but also land transport, heavy industry and households. The two-stroke engine's ability to burn methanol, ammonia, ethanol, and biofuels ensures that the global fleet can adapt to the most available and cost-competitive green fuels as they emerge. The shift from a single-engine focus to an integrated ship energy system—incorporating hybridization, shaft generators, and waste heat recovery—is essential for making the use of zero-carbon fuels economically viable. The IMO's 2023 Strategy and the subsequent Net-Zero Framework provide the long-term certainty required for shipowners to invest in expensive newbuilds and retrofits. Short-term goals will be met primarily through efficiency improvements and slow steaming. While biofuels and alcohols will lead the transition in the current decade, ammonia and potentially nuclear propulsion represent the long-term solutions for a truly zero-carbon maritime industry by mid-century. Nuclear propulsion would likely render two-stroke slow-speed "diesel" engines obsolete.

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