Review of types of marine diesel engines and their applications in modern ships

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ABSTRACT

Marine diesel engines remain the dominant power source for commercial shipping, accounting for approximately 90% of the world's fleet propulsion systems. This review article provides a comprehensive examination of marine diesel engine classification, operational characteristics, and applications across various vessel types. The classification is based on rotational speed: low-speed two-stroke engines (below 300 rpm), medium-speed four-stroke engines (300–1000 rpm), and high-speed four-stroke engines (above 1000 rpm). Each engine category exhibits distinct thermal efficiency, fuel consumption characteristics, and suitability for specific maritime applications. Low-speed two-stroke crosshead engines achieve thermal efficiencies exceeding 55% and are predominantly employed in tankers, bulk carriers, and container ships. Medium-speed engines offer versatility for ferries, offshore support vessels, and cruise ships, while high-speed engines serve smaller craft requiring rapid response. The article examines emission control technologies, including selective catalytic reduction (SCR), exhaust gas recirculation (EGR), and exhaust gas cleaning systems (EGCS), that enable compliance with the International Maritime Organization (IMO) MARPOL Annex VI regulations. Furthermore, the review explores dual-fuel engine technologies capable of operating on liquefied natural gas (LNG), methanol, and future ammonia applications. Through analysis of specific fuel oil consumption (SFOC) data and comparative performance metrics, this article provides marine engineers and naval architects with essential knowledge for optimal engine selection based on vessel type, operational profile, and regulatory requirements.

Keywords: marine diesel engine; two-stroke engine; four-stroke engine; specific fuel oil consumption; emission control; MARPOL Annex VI; dual-fuel engine; exhaust gas cleaning

1. INTRODUCTION

The global maritime transport industry handles approximately 90% of international trade by volume, making it the backbone of the global economy [1]. At the heart of this vast transportation network lies the marine diesel engine, a technology that has undergone remarkable evolution since Rudolf Diesel patented the compression-ignition engine in 1893 [2]. Modern marine diesel engines represent the culmination of more than a century of engineering refinement, delivering thermal efficiencies that surpass any other practical thermal prime mover, with the most advanced two-stroke low-speed engines achieving brake thermal efficiencies exceeding 55% [3].

The predominance of diesel engines in maritime applications stems from their exceptional reliability, fuel versatility, and economic operation. Unlike their counterparts in automotive applications, marine diesel engines are designed for continuous operation over extended periods, often running for months between overhauls while consuming the lowest-cost fuel available—heavy fuel oil (HFO) with viscosities up to 380 cSt [4]. The ability to burn residual fuels, which are byproducts of the crude oil refining process, provides ship operators with significant economic advantages, as HFO typically costs 30–50% less than distillate marine fuels [5].

The selection of an appropriate marine diesel engine for a given vessel represents one of the most critical decisions in ship design, affecting not only the initial capital expenditure but also the operational economics, environmental compliance, and maintenance requirements throughout the vessel's 20–25 year service life [6]. Engine selection must account for vessel type, size, operational profile, fuel availability, emission regulations, and the specific power requirements dictated by hull resistance characteristics and propeller optimization. The complexity of this decision-making process has increased substantially in recent years due to the implementation of stringent emission regulations under IMO MARPOL Annex VI and the emergence of alternative fuels including liquefied natural gas (LNG), methanol, and ammonia [7].

This review article aims to provide a comprehensive examination of marine diesel engine types, their fundamental operating principles, performance characteristics, and applications across the spectrum of modern commercial vessels. The article synthesizes recent technical literature and manufacturer data to present a structured analysis that supports informed engine selection decisions. By examining the relationship between engine architecture, fuel consumption, emission characteristics, and regulatory compliance, this review contributes to the broader understanding of marine propulsion technology in an era of transition toward decarbonization.

2. CLASSIFICATION OF MARINE DIESEL ENGINES

2.1 Classification by Operating Speed

Marine diesel engines are broadly classified into three categories based on their rated rotational speed: low-speed, medium-speed, and high-speed engines. This classification system, universally adopted by engine manufacturers and classification societies, provides the primary framework for understanding engine characteristics and matching engines to vessel applications [8]. The speed classification directly influences engine architecture, thermodynamic cycle efficiency, power density, fuel type compatibility, and the method of propeller drive. Figure 1 illustrates the comprehensive classification of marine diesel engines based on operating speed, along with their key characteristics and typical applications.

Low-speed engines operate at rotational speeds below 300 rpm, with the largest engines turning at rates as low as 50–120 rpm [9]. These engines universally employ the two-stroke thermodynamic cycle and feature crosshead construction, in which the piston rod connects to a crosshead assembly that translates reciprocating motion to the connecting rod while maintaining purely linear piston movement. The crosshead design enables extremely long stroke-to-bore ratios, typically ranging from 2.5:1 to 4.2:1, which contributes to the exceptional thermal efficiency of these engines [10]. The long stroke length results in a lower rotational speed for a given mean piston speed, making direct coupling to the propeller shaft possible without an intermediate gearbox. This direct-drive configuration eliminates gearbox losses—typically 2–4% of transmitted power—and enables the use of larger, more efficient propellers that operate at optimal rotational speeds of 50–130 rpm [11].

Medium-speed engines operate in the range of 300–1000 rpm and universally employ the four-stroke thermodynamic cycle with trunk piston construction [12]. These engines require a reduction gearbox to match the propeller's optimal rotational speed, introducing mechanical losses but offering significant advantages in terms of power density, engine room height requirements, and operational flexibility. Medium-speed engines can be arranged in multiple-engine configurations driving a single propeller through combining gearboxes, providing redundancy and the ability to optimize engine loading for varying power demands. The power output of individual medium-speed engines typically ranges from 500 kW to 20 MW, with the largest medium-speed installations comprising multiple engines reaching combined outputs of 40 MW or more [13].

High-speed engines operate above 1000 rpm, with some small marine diesel engines reaching speeds of 3000–3600 rpm [14]. These four-stroke trunk piston engines prioritize power-to-weight ratio and compact dimensions over fuel efficiency. High-speed engines exclusively drive propellers through reduction gearboxes with ratios typically exceeding 3:1. Their compact size and rapid starting capability make them suitable for vessels where space constraints, weight limitations, or requirements for rapid maneuverability take precedence over fuel economy. Table 1 provides a detailed comparison of the technical characteristics across the three engine speed categories.

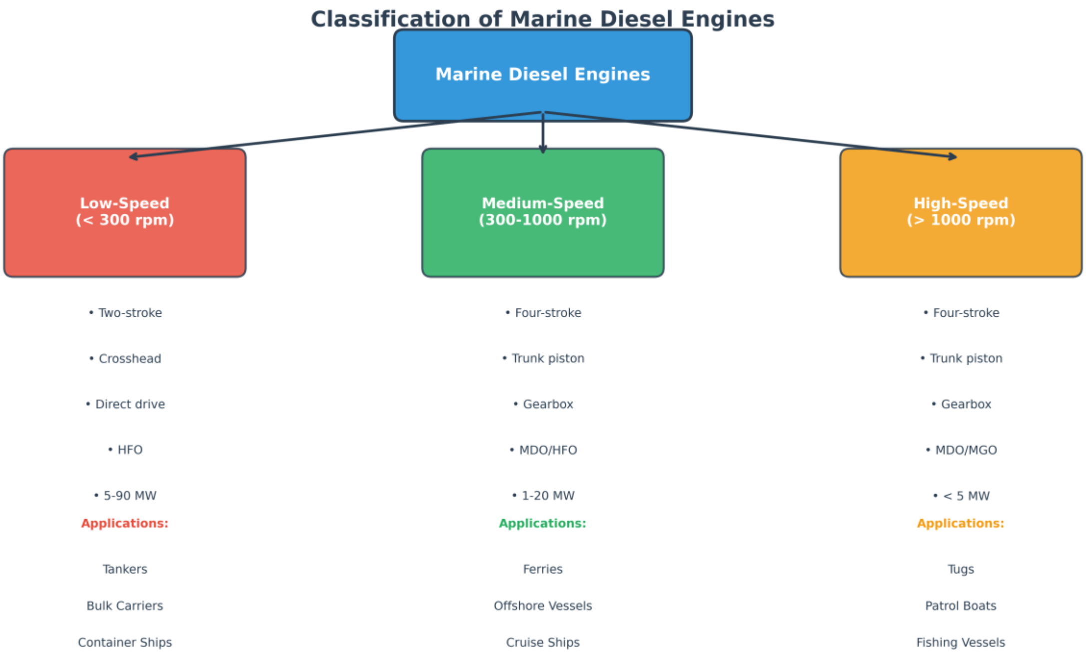

Figure 1. Classification of marine diesel engines by speed, characteristics, and applications.

Table 1. Technical characteristics of marine diesel engines by speed classification [15]

Parameter	**Low-Speed (< 300 rpm)**	**Medium-Speed (300–1000 rpm)**	**High-Speed (> 1000 rpm)**
Cycle type	Two-stroke	Four-stroke	Four-stroke
Piston type	Crosshead	Trunk piston	Trunk piston
Drive method	Direct drive	Gearbox	Gearbox
Typical bore (mm)	260–980	260–600	130–280
Stroke-to-bore ratio	2.5–4.2	1.0–1.5	1.0–1.4
Power range per unit (kW)	5,000–90,000	500–20,000	100–5,000
Typical SFOC (g/kWh)	155–175	175–210	210–260
Thermal efficiency (%)	50–55+	45–50	38–45
Primary fuel	HFO	MDO/HFO	MDO/MGO
Typical applications	Tankers, bulk carriers, container ships	Ferries, cruise ships, offshore vessels	Tugs, patrol boats, pilot boats

2.2 Classification by Thermodynamic Cycle

The thermodynamic cycle represents a fundamental distinction between marine diesel engine types, with two-stroke and four-stroke cycles offering different trade-offs between power density, efficiency, and complexity. Two-stroke engines complete the thermodynamic cycle in a single crankshaft revolution, while four-stroke engines require two complete revolutions [16]. This fundamental difference has profound implications for engine design, scavenging methodology, and application suitability.

Two-stroke marine engines exclusively employ uniflow scavenging, in which pressurized air enters the cylinder through scavenge ports near the bottom of the cylinder liner and exhaust gases exit through a valve in the cylinder cover [17]. This scavenging method provides efficient cylinder purging with minimal short-circuiting of fresh air to the exhaust. Modern two-stroke engines utilize constant-pressure turbocharging, in which exhaust gases from all cylinders discharge into a common receiver that maintains nearly constant pressure, driving the turbocharger turbine. The scavenge air is compressed and cooled before entering the cylinder, with modern systems achieving scavenge air pressures exceeding 4 bar at full load [18]. The elimination of the inlet and exhaust strokes in the two-stroke cycle allows every downward piston movement to produce power, contributing to the high power density and uniform torque characteristics that make these engines suitable for direct propeller drive.

Four-stroke engines employ the more conventional intake, compression, expansion, and exhaust strokes sequence, with each cylinder firing once every two crankshaft revolutions [19]. This architecture provides more time for complete scavenging and allows for more complex valve timing strategies, including the Miller cycle, which has gained prominence as an emission reduction technique. In the Miller cycle, the intake valves close earlier than in a conventional four-stroke engine, reducing the effective compression ratio while maintaining the expansion ratio. This approach reduces peak combustion temperatures and consequently lowers NOx formation, with extreme Miller timing capable of achieving 40–50% NOx reduction compared to conventional timing [20]. Four-stroke engines also facilitate the implementation of exhaust gas recirculation (EGR) more readily than two-stroke engines, as the discrete exhaust stroke provides a clearer separation between exhaust and intake processes.

3. LOW-SPEED TWO-STROKE ENGINES

3.1 Design Characteristics and Operating Principles

Low-speed two-stroke crosshead engines represent the pinnacle of marine diesel engine development in terms of thermal efficiency and power output. These engines are manufactured by a limited number of specialized companies, with MAN Energy Solutions and Wärtsilä collectively commanding over 70% of the global market share for large two-stroke propulsion engines [21]. The crosshead design, which separates the combustion space above the piston from the crankcase below, allows the piston rod to operate with purely vertical motion, eliminating the side thrust on the cylinder liner that occurs in trunk piston engines [22]. This design feature enables the extremely long stroke lengths that contribute to high thermal efficiency while minimizing cylinder liner wear.

The engine block of a modern low-speed two-stroke engine consists of a bedplate, frame boxes, and cylinder block, all held together by vertical tie rods that pre-tension the assembly against the firing pressure loads [23]. The bedplate, typically fabricated from welded steel, supports the main bearings and provides the structural foundation for the entire engine. Frame boxes house the crosshead guides and transfer the combustion forces to the bedplate. The cylinder block contains the scavenge air ports, cooling water passages, and mounting provisions for the cylinder covers, fuel injection equipment, and exhaust valves. This modular construction facilitates maintenance by allowing individual components to be accessed without disturbing adjacent cylinders.

Fuel injection in modern two-stroke engines employs common-rail technology, in which fuel is pressurized by high-pressure pumps and stored in a common rail at pressures exceeding 1000 bar [24]. Electronic control of the fuel injectors enables precise timing, multiple injection events per cycle, and rate shaping to optimize combustion for varying load conditions. The ME-series engines from MAN Energy Solutions and the RT-flex engines from Wärtsilä represent the current state of electronic control in two-stroke marine engines, replacing the traditional camshaft-driven fuel pumps and mechanically actuated exhaust valves with electronically controlled hydraulic systems [25]. This electronic control capability enables dynamic optimization of combustion parameters including injection timing, injection pressure, injection rate profile, and exhaust valve closing timing, resulting in improved fuel efficiency and reduced emissions across the operating envelope.

3.2 Performance Characteristics and Efficiency

The thermal efficiency of low-speed two-stroke engines exceeds that of all other practical thermal prime movers, with the most advanced engines achieving brake thermal efficiencies of 54–55% at optimum load conditions [26]. This exceptional efficiency stems from multiple design features: the long stroke-to-bore ratio that maximizes expansion work extraction, the uniflow scavenging system that provides efficient cylinder charging, the high compression ratios enabled by the crosshead architecture, and the ability to optimize combustion through electronic control of fuel injection and exhaust valve timing.

Specific fuel oil consumption (SFOC) provides the standard metric for quantifying engine efficiency in marine applications, expressing the mass of fuel consumed per unit of power output, typically in grams per kilowatt-hour (g/kWh) [27]. Modern large-bore two-stroke engines achieve SFOC values of 155–175 g/kWh at rated load when operating on HFO, with the optimum efficiency typically occurring at loads between 75% and 85% of maximum continuous rating (MCR) [28]. The SFOC increases at both lower and higher loads due to factors including reduced thermodynamic efficiency at partial load, increased relative heat losses at low load, and compromised combustion quality at high load. Figure 2 illustrates the typical SFOC characteristics as a function of engine load for the three engine speed categories, showing the superior efficiency of low-speed two-stroke engines across the operational range.

The relationship between SFOC and engine load exhibits a characteristic U-shaped curve, with minimum fuel consumption occurring at intermediate load levels [29]. At loads below approximately 50% MCR, the SFOC increases significantly due to the disproportionate effect of fixed losses including pumping work, friction, and heat transfer relative to the reduced power output. At loads approaching 100% MCR, combustion quality may deteriorate due to thermal loading constraints, and the turbocharger may approach its surge limit, causing a modest increase in SFOC. This load-dependent efficiency characteristic has important implications for vessel operational strategies, particularly in the context of slow steaming, where vessels intentionally operate at reduced speeds to save fuel.

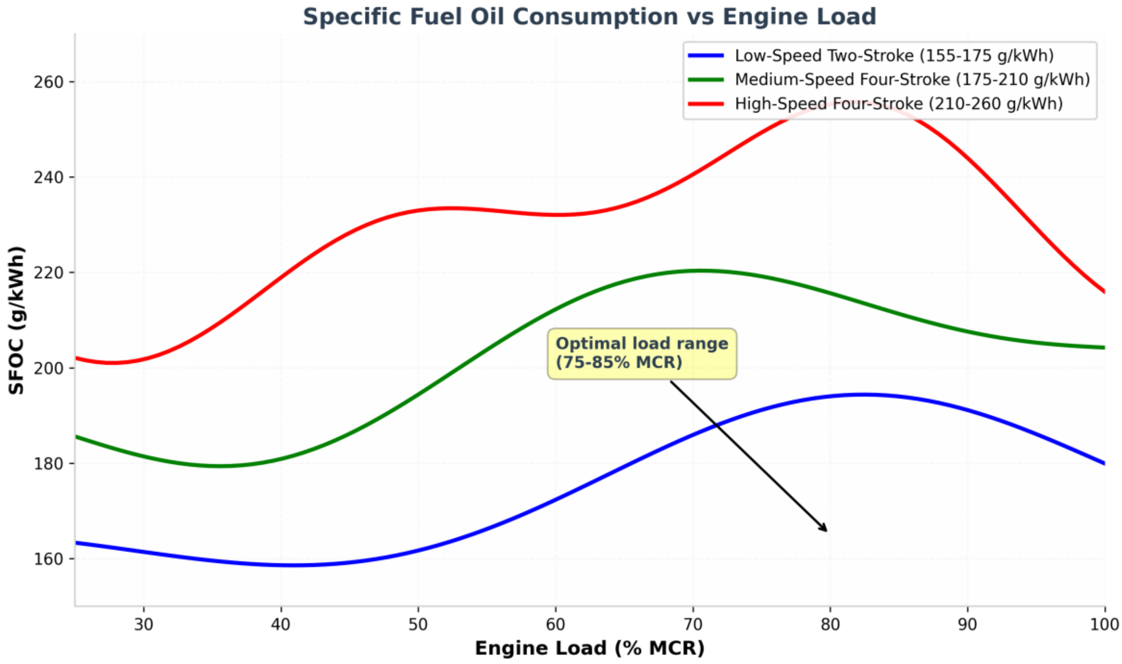

Figure 2. Specific fuel oil consumption (SFOC) as a function of engine load for different marine diesel engine types.

3.3 Applications in Large Commercial Vessels

Low-speed two-stroke engines dominate the propulsion of large commercial vessels including crude oil tankers, product tankers, bulk carriers, and container ships [30]. The direct-drive configuration, in which the engine crankshaft connects directly to the propeller shaft without an intermediate gearbox, provides simplicity and reliability that is particularly valued in long-haul maritime transport. The ability to burn low-cost HFO further reinforces the economic advantage of these engines for vessel types where fuel costs represent a significant portion of operating expenses.

For crude oil tankers and bulk carriers, single-engine single-propeller configurations predominate, with engine outputs ranging from approximately 10 MW for Handysize vessels to over 80 MW for Very Large Crude Carriers (VLCCs) and Capesize bulk carriers [31]. Container ships, particularly the largest Ultra Large Container Vessels (ULCVs) with capacities exceeding 24,000 TEU, may employ twin-engine configurations or single engines rated at 60–90 MW [32]. The selection between single and twin-engine arrangements involves trade-offs between redundancy, machinery space requirements, initial cost, and operational flexibility. Container ships typically require shaft generators or power take-off (PTO) systems to provide electrical power for refrigerated containers, which can amount to 6 MW or more on the largest vessels.

4. MEDIUM-SPEED FOUR-STROKE ENGINES

4.1 Design Characteristics and Versatility

Medium-speed four-stroke engines occupy a central position in marine propulsion, offering a balance between the exceptional efficiency of low-speed engines and the compactness of high-speed engines. These engines are characterized by trunk piston construction, in which the connecting rod connects directly to the piston without an intermediate crosshead, resulting in a more compact design that accepts some side thrust on the cylinder liner [33]. The four-stroke cycle provides one power stroke per two crankshaft revolutions, requiring a higher rotational speed to achieve a given mean piston speed compared to two-stroke engines. Medium-speed engines typically employ bore diameters ranging from 260 mm to 600 mm, with cylinder counts varying from 6 to 24 cylinders in Vee or inline configurations.

The versatility of medium-speed engines stems from their adaptability to multiple roles within the propulsion system. A single medium-speed engine can serve as the main propulsion engine through a reduction gearbox, as an auxiliary generator set, or as part of a diesel-electric propulsion system [34]. This flexibility enables shipyards and operators to standardize on a single engine type for multiple applications, simplifying spare parts logistics and maintenance procedures. Leading manufacturers of medium-speed marine engines include Wärtsilä, MAN Energy Solutions, Caterpillar (MAK), and Cummins, with each manufacturer offering engine families optimized for specific applications and fuel types [35].

Modern medium-speed engines incorporate advanced technologies including two-stage turbocharging, common-rail fuel injection, and sophisticated engine management systems. Two-stage turbocharging, in which exhaust gases sequentially drive high-pressure and low-pressure turbines connected to separate compressors, enables higher boost pressures and improved efficiency across the operating range [36]. This technology is particularly important for achieving IMO Tier III NOx compliance through Miller cycle operation, as the increased boost pressure compensates for the reduced effective compression ratio. The common-rail fuel injection systems used in modern medium-speed engines provide injection pressures exceeding 2000 bar, enabling precise control over injection timing, duration, and rate shaping for optimized combustion and emission characteristics.

4.2 Applications in Specialized Vessels

Medium-speed engines find extensive application in vessel types where operational requirements differ from the steady-state long-haul operation of bulk carriers and tankers. Ferries, roll-on/roll-off (Ro-Ro) vessels, and cruise ships require propulsion systems capable of rapid load changes, frequent maneuvering, and operation across a wide speed range [37]. The ability to combine multiple medium-speed engines through combining gearboxes provides redundancy and enables optimization of engine loading for varying power demands. When full power is required for high-speed transit, all engines can operate; during port approach or loitering, a subset of engines can provide the required power while maintaining each operating engine near its optimum load point.

Offshore support vessels (OSVs), including platform supply vessels, anchor handling tug supply vessels, and construction support vessels, represent another significant application for medium-speed engines. These vessels require high bollard pull for towing and anchor handling operations, precise station-keeping capability through dynamic positioning systems, and reliable operation in harsh weather conditions [38]. Diesel-electric propulsion systems, in which medium-speed diesel engines drive generators that supply electrical power to azimuthing thrusters, have become the standard configuration for sophisticated OSVs. This arrangement decouples engine speed from propeller speed, enabling the engines to operate at constant speed for optimal efficiency while the propulsion system responds dynamically to varying load demands.

Cruise ships present unique propulsion requirements due to their high electrical power demands for hotel services, air conditioning, and entertainment facilities, often exceeding the propulsion power requirement [39]. Modern cruise ships typically employ multiple medium-speed diesel generators in a diesel-electric configuration, with total installed generator capacity reaching 60–90 MW for the largest vessels. The requirement for minimal vibration and noise transmission to passenger accommodations favors medium-speed engines with their smoother torque characteristics and lower vibration levels compared to low-speed engines. The ability to locate diesel generators throughout the vessel, rather than concentrating propulsion power in a single engine room, also provides design flexibility for optimizing space utilization and vessel layout.

5. HIGH-SPEED FOUR-STROKE ENGINES

5.1 Characteristics and Operational Role

High-speed marine diesel engines, operating at rotational speeds above 1000 rpm, occupy the lower end of the marine engine power spectrum while offering unique advantages in specific applications. These engines prioritize power-to-weight ratio, compact dimensions, and rapid response over fuel efficiency [40]. The high rotational speed enables significant power output from relatively small displacement, making these engines suitable for vessels where machinery space is severely constrained or where weight reduction provides operational advantages. High-speed engines exclusively employ the four-stroke cycle with trunk piston construction and drive propellers through reduction gearboxes with ratios typically ranging from 2:1 to 4:1.

The construction of high-speed marine engines shares many features with heavy-duty automotive and industrial diesel engines, with adaptations for the marine environment including enhanced corrosion protection, seawater-cooled heat exchangers, and marine-class certification from classification societies [41]. Cylinder bore diameters typically range from 100 mm to 200 mm, with engine configurations spanning inline 4-cylinder to Vee 16-cylinder arrangements. Power outputs per engine range from approximately 100 kW for small auxiliary generators to 4000 kW for the largest high-speed propulsion engines. Multiple engines can be combined through gearboxes for higher power requirements, although this practice becomes less common as power demands exceed 5 MW, where medium-speed engines offer superior efficiency and durability.

5.2 Applications in Small Vessels

The primary applications for high-speed diesel engines include harbor tugs, pilot boats, patrol vessels, fishing boats, and small commercial craft [42]. These vessels require rapid acceleration, high maneuverability, and the ability to operate effectively across a wide speed range. Harbor tugs, in particular, demand propulsion systems capable of delivering maximum bollard pull for ship handling operations while also providing sufficient free-running speed for transit between assignments. High-speed engines meet these requirements through their ability to rapidly accept load changes and their compatibility with controllable-pitch propeller (CPP) systems that enable efficient operation across varying speed and load conditions.

Fishing vessels represent a significant market for high-speed marine diesel engines, with requirements varying based on fishing method and vessel size [43]. Trawlers and purse seiners require reliable propulsion for extended periods of towing and maneuvering, while longline and gillnet vessels may operate at lower speeds for extended durations. The ability of high-speed engines to run on marine diesel oil (MDO) or marine gas oil (MGO) simplifies fuel management for smaller vessels that may not have the heating and purification equipment necessary for HFO operation. The lower initial cost of high-speed engines compared to medium-speed and low-speed alternatives also makes them economically attractive for smaller vessels with limited capital budgets.

Military and paramilitary applications including naval patrol boats, coast guard cutters, and fast intervention craft favor high-speed diesel engines for their compact size, rapid starting capability, and survivability features [44]. Many military vessels employ combined diesel and gas turbine (CODAG) or combined diesel or gas turbine (CODOG) propulsion arrangements, in which high-speed diesel engines provide efficient cruise propulsion while gas turbines deliver maximum power for sprint operations. The diesel engines in these applications must be capable of rapid starting and load acceptance to support operational requirements.

6. EMISSION CONTROL TECHNOLOGIES AND REGULATORY COMPLIANCE

6.1 IMO MARPOL Annex VI Regulations

The International Maritime Organization has established progressively stringent regulations for air emissions from ships through Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL). These regulations address sulfur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM), and greenhouse gas emissions, with implementation timelines that have significantly influenced marine engine technology development [45]. The NOx regulations, specified in Regulation 13 of MARPOL Annex VI, establish tiered emission limits based on engine speed, with progressively stricter limits applicable to engines installed on vessels constructed after specified dates.

The NOx emission limits are structured in three tiers. Tier I, applicable to engines installed on ships built between 2000 and 2010, established baseline limits ranging from 17.0 g/kWh for engines below 130 rpm to 9.8 g/kWh for engines at or above 2000 rpm [46]. Tier II, applicable to engines installed on ships built from 2011 onward, requires a 20% reduction from Tier I levels across all engine speeds. Tier III, applicable to engines installed on ships operating in Emission Control Areas (ECAs) built from 2016 onward, mandates an 80%

reduction from Tier I levels, representing the most stringent NOx emission requirements for marine diesel engines. Figure 3 presents the IMO NOx emission limits across the three regulatory tiers as a function of engine speed.

The sulfur regulations, specified in Regulation 14 of MARPOL Annex VI, limit the sulfur content of fuel oil used on board ships. The global sulfur cap was reduced from 3.50% to 0.50% on January 1, 2020, a regulatory change commonly referred to as 'IMO 2020' [47]. Within designated Emission Control Areas, which currently include the Baltic Sea, North Sea, North American coast, and Caribbean Sea, the sulfur limit is 0.10%. Ship operators can comply with these regulations by using low-sulfur fuels, by installing exhaust gas cleaning systems (scrubbers) that reduce SOx emissions to equivalent levels while continuing to burn HFO, or by using alternative fuels such as LNG that inherently contain minimal sulfur.

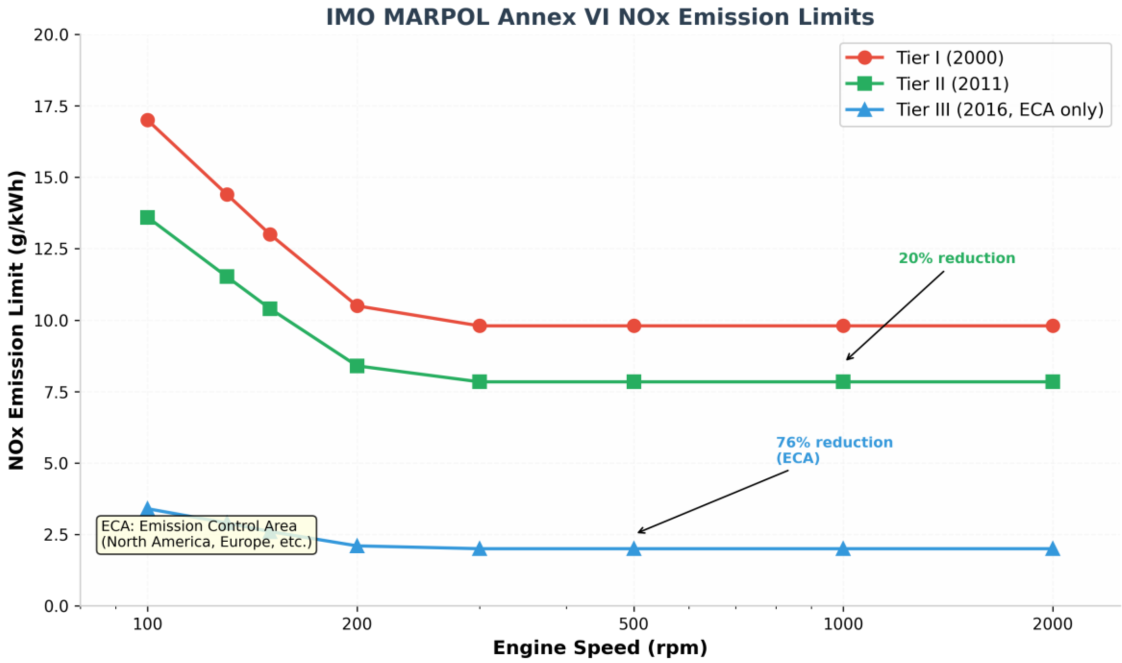

Figure 3. IMO MARPOL Annex VI NOx emission limits for marine diesel engines across Tier I, Tier II, and Tier III regulations.

6.2 NOx Reduction Technologies

Compliance with IMO NOx regulations, particularly the stringent Tier III limits applicable in ECAs, requires the implementation of emission reduction technologies that address the formation mechanisms of nitrogen oxides during combustion. The two primary technological approaches for achieving Tier III compliance are selective catalytic reduction (SCR) and exhaust gas recirculation (EGR), with dual-fuel engines capable of operating on natural gas providing a third compliance pathway [48].

Selective catalytic reduction systems inject a urea-water solution into the exhaust stream upstream of a catalytic converter. The urea decomposes to form ammonia, which reacts with NOx on the catalyst surface to produce nitrogen and water [49]. SCR systems can achieve NOx reduction efficiencies of 85–95%, making them capable of meeting Tier III requirements from a Tier II baseline. The primary challenges associated with SCR operation include the need to maintain exhaust gas temperatures within the catalyst operating window of approximately

300–450°C, the requirement for urea storage and handling infrastructure, and the potential for ammonia slip if injection rates are not precisely controlled. SCR systems add significant complexity and cost to the propulsion plant, with installation costs typically ranging from $300,000 to $800,000 depending on engine size and system configuration.

Exhaust gas recirculation reduces NOx formation at the source by recirculating a portion of the exhaust gas back into the engine intake, diluting the oxygen concentration and increasing the heat capacity of the cylinder charge [50]. These effects reduce peak combustion temperatures, which in turn decreases thermal NOx formation. EGR systems can achieve 50–60% NOx reduction, sufficient to meet Tier II requirements without additional aftertreatment but generally requiring combination with other measures for Tier III compliance in diesel mode. The primary challenges of EGR in marine applications include fouling of the EGR cooler by sulfur compounds in the exhaust, increased particulate emissions at high EGR rates, and the potential for corrosion of engine components due to the acidic condensate formed when cooling high-sulfur exhaust gases.

6.3 SOx Compliance Strategies

The implementation of the IMO 2020 sulfur cap has fundamentally altered the fuel landscape for marine shipping, creating three primary compliance pathways for ship operators [51]. The first and simplest approach involves switching to low-sulfur fuels, either very low sulfur fuel oil (VLSFO) with sulfur content at or below 0.50% or marine gas oil (MGO) with sulfur content at or below 0.10%. VLSFO emerged as the dominant compliance solution following IMO 2020, with refineries blending residual and distillate components to produce fuels meeting the 0.50% sulfur limit while maintaining compatibility with existing engine and fuel system designs [52]. The price differential between VLSFO and conventional HFO has varied significantly based on crude oil prices and refining capacity, typically ranging from $50 to $150 per tonne.

Exhaust gas cleaning systems, commonly known as scrubbers, provide an alternative compliance method that enables continued operation on HFO while reducing SOx emissions to levels equivalent to low-sulfur fuel operation [53]. Wet scrubber systems, which dominate the marine market, use water as the scrubbing medium to remove sulfur compounds from exhaust gases. Open-loop scrubbers use seawater as the scrubbing medium and discharge the treated washwater overboard, while closed-loop scrubbers recirculate fresh water treated with alkaline chemicals, with no discharge to the sea. Hybrid scrubbers can operate in either open-loop or closed-loop mode, providing operational flexibility based on local regulations regarding washwater discharge. Figure 4 illustrates the IMO 2020 SOx compliance strategies available to ship operators, comparing the characteristics of each approach.

The third compliance pathway involves the use of alternative fuels that inherently contain minimal or zero sulfur. LNG has emerged as the most commercially viable alternative fuel for marine applications, with sulfur content effectively zero and NOx emissions approximately 85% lower than HFO operation when used in Otto-cycle dual-fuel engines [54]. Methanol represents another alternative fuel option, with sulfur-free composition and the advantage of liquid storage at ambient temperatures. Ammonia and hydrogen are being developed as future zero-carbon fuel options, although significant technical and infrastructure challenges remain before these fuels achieve widespread commercial application.

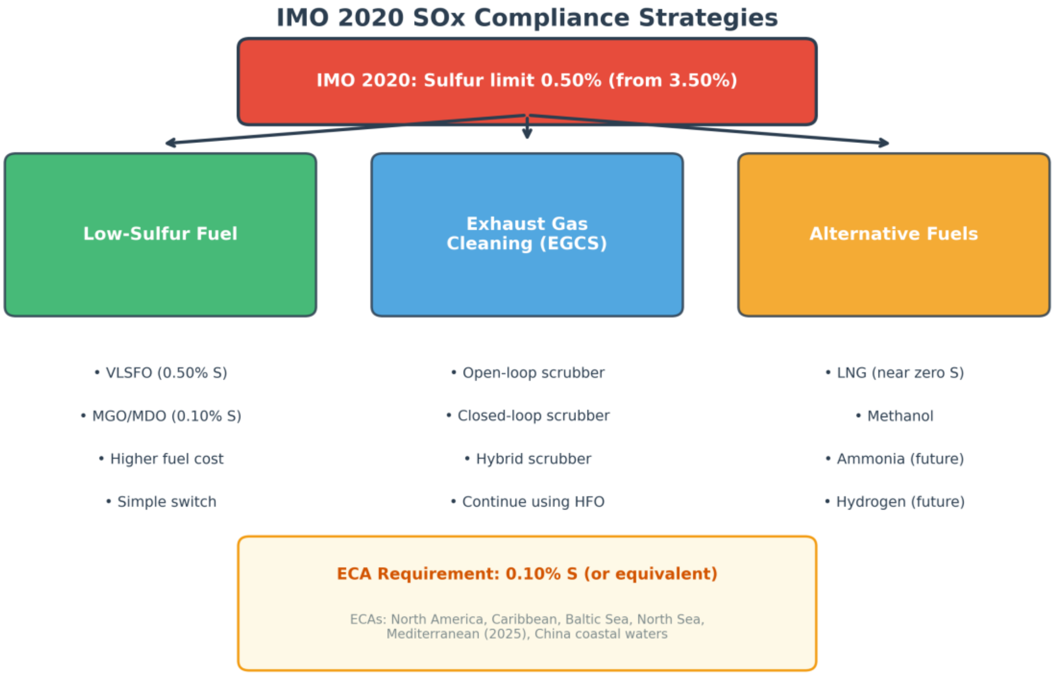

Figure 4. IMO 2020 SOx compliance strategies: low-sulfur fuel, exhaust gas cleaning systems (EGCS), and alternative fuels.

7. DUAL-FUEL AND ALTERNATIVE FUEL ENGINES

7.1 LNG Dual-Fuel Technology

Dual-fuel engines capable of operating on both conventional liquid fuels and natural gas have emerged as a critical technology for the maritime energy transition, offering ship operators fuel flexibility and a pathway to reduced emissions [55]. LNG dual-fuel engines can operate in gas mode, using natural gas as the primary fuel with a small quantity of pilot diesel fuel for ignition, or in diesel mode using conventional liquid fuel. The ability to switch between fuel modes provides operational flexibility, allowing vessels to use LNG when available and cost-effective while maintaining the capability to operate on liquid fuels when LNG bunkering infrastructure is unavailable.

Two principal combustion concepts exist for LNG dual-fuel engines: the diesel cycle (compression ignition) and the Otto cycle (spark ignition or lean-burn) [56]. Diesel-cycle dual-fuel engines inject high-pressure natural gas directly into the combustion chamber at the end of the compression stroke, where it ignites upon contact with the hot pilot diesel spray. This concept, exemplified by MAN Energy Solutions' ME-GI engines, maintains the high thermal efficiency of conventional diesel engines while offering the emission benefits of natural gas fuel. Otto-cycle dual-fuel engines premix natural gas with intake air before compression, with ignition provided by a small diesel pilot injection or spark plugs. Wärtsilä's DF engines employ this concept, achieving lower NOx emissions than diesel-cycle concepts due to the lean premixed combustion but with slightly lower thermal efficiency.

The environmental benefits of LNG as a marine fuel include near-zero sulfur oxide emissions, approximately 85% reduction in NOx emissions (Otto cycle) or 20% reduction (diesel cycle) compared to HFO, and approximately 20–25% reduction in CO2 emissions due to the lower carbon-to-hydrogen ratio of methane compared to liquid hydrocarbon fuels [57]. However, the use of LNG also presents challenges including methane slip—unburned methane escaping to the atmosphere through the exhaust—which can offset some of the greenhouse gas benefits due to methane's high global warming potential. Modern engine designs have reduced methane slip to levels below 0.2% of fuel consumption in diesel-cycle engines, while Otto-cycle engines may experience slip levels of 0.5–1.0% depending on load and operating mode.

7.2 Methanol and Ammonia as Future Fuels

Methanol has gained significant attention as a marine fuel due to its liquid state at ambient temperatures, which simplifies storage and handling compared to cryogenic LNG or compressed hydrogen [58]. Methanol contains no sulfur and produces minimal particulate emissions during combustion. When produced from renewable sources (green methanol), it offers a pathway to carbon-neutral shipping. MAN Energy Solutions and Wärtsilä have both developed methanol-capable engine designs, with the first methanol-powered container ships entering service in 2023 [59]. The energy density of methanol is approximately half that of HFO on a volume basis, requiring approximately twice the fuel tank capacity for equivalent range, which presents design challenges for vessel layout.

Ammonia represents a promising long-term fuel option for zero-carbon shipping, as it contains no carbon and therefore produces no CO2 emissions during combustion [60]. Ammonia can be synthesized from hydrogen and nitrogen using renewable electricity, providing a pathway to fully carbon-free fuel production. The use of ammonia as a marine fuel presents significant technical challenges including its high toxicity, low flame speed, narrow flammability limits, and high NOx and N2O emissions during combustion [61]. Research and development efforts are focused on developing ammonia-fueled engine concepts, safe fuel handling systems, and exhaust aftertreatment technologies to address these challenges. Major engine manufacturers have announced plans for commercially available ammonia engines by 2025–2026, with the first ammonia-powered vessels expected to enter service in the late 2020s.

8. ENGINE SELECTION CRITERIA FOR MODERN SHIPS

8.1 Vessel-Specific Considerations

The selection of a marine diesel engine for a specific vessel application requires systematic evaluation of multiple interrelated factors that determine the optimal propulsion system configuration [62]. The vessel type and operational profile establish the foundational requirements for engine power, speed characteristics, and fuel type. Tankers and bulk carriers operating on long-haul routes at steady speeds prioritize fuel efficiency and reliability, making low-speed two-stroke engines the natural choice. Ferries and cruise ships operating on schedules with frequent port calls require propulsion systems capable of rapid maneuvering and load changes, favoring medium-speed engines with controllable-pitch propellers or diesel-electric configurations.

The physical constraints of the vessel impose practical limitations on engine selection. Engine room height may preclude the installation of low-speed engines with their tall cylinder blocks and overhead-mounted exhaust systems. Machinery space length and width constraints may influence the selection between inline and Vee engine configurations or between single and multiple-engine arrangements. Weight considerations affect vessel stability and cargo capacity, with high-speed engines offering advantages in applications where machinery weight must be minimized.

Fuel availability and cost structure significantly influence engine selection decisions. Vessels operating on fixed routes with reliable access to LNG bunkering infrastructure may justify the additional capital cost of dual-fuel engines, while vessels trading globally on unpredictable routes may require the fuel flexibility provided by engines capable of operating on multiple liquid fuel grades. The price differential between HFO and low-sulfur alternatives affects the economic viability of scrubber installations versus fuel switching strategies. Table 2 provides a summary of engine selection considerations for major vessel categories.

Table 2. Marine diesel engine selection by vessel type [63]

Vessel Type	**Preferred Engine Type**	**Typical Power Range**	**Drive Configuration**	**Key Selection Factors**
Crude oil tanker (VLCC)	Low-speed two-stroke	20–35 MW	Single engine, direct drive	Fuel efficiency, reliability, low OPEX
Bulk carrier (Capesize)	Low-speed two-stroke	15–25 MW	Single engine, direct drive	Fuel efficiency, simplicity, HFO compatibility
Container ship (ULCV)	Low-speed two-stroke	50–90 MW	Single/twin engine, direct drive	Maximum power, SFOC, shaft generator PTO
Ferry (Ro-Pax)	Medium-speed four-stroke	10–40 MW	Multiple engines, CPP or diesel-electric	Maneuverability, redundancy, quick response
Cruise ship	Medium-speed four-stroke	30–90 MW	Diesel-electric, podded propulsors	Low vibration, high electrical demand, redundancy
Offshore support vessel	Medium-speed four-stroke	5–20 MW	Diesel-electric, azimuth thrusters	DP capability, redundancy, power management

Harbor tug	High-speed four-stroke	2–5 MW	Single/twin engine, CPP	Bollard pull, acceleration, compact size
Fishing trawler	Medium/high-speed four-stroke	1–5 MW	Single engine, CPP	Reliability, fuel availability, OPEX

8.2 Economic Analysis and Lifecycle Cost

The economic evaluation of marine engine options extends beyond the initial purchase price to encompass the total cost of ownership over the vessel's operational life. Fuel costs typically represent 60–80% of total vessel operating costs, making SFOC a critical parameter in lifecycle cost analysis [64]. The capital cost difference between engine options must be weighed against the present value of fuel cost savings over the vessel's service life. Low-speed two-stroke engines, despite their higher initial cost compared to medium-speed alternatives for equivalent power, typically deliver superior lifecycle economics for vessels with high annual operating hours due to their lower SFOC.

Maintenance costs represent another significant component of lifecycle economics, with low-speed engines generally requiring overhauls at intervals of 2–3 years depending on operating hours, while medium-speed engines may require more frequent maintenance due to their higher rotational speeds and trunk piston construction [65]. The availability and cost of spare parts, the geographic distribution of service networks, and the manufacturer's warranty terms all influence maintenance cost projections. Engine reliability and the probability of unscheduled downtime also carry economic implications, particularly for vessels operating on time-sensitive schedules.

The regulatory environment adds a dynamic element to lifecycle cost analysis, as future emission regulations may require engine modifications, aftertreatment system installations, or fuel switching that affect operating costs [66]. Engines designed with provisions for future retrofit, such as dual-fuel capability or SCR readiness, may command a premium initial cost but provide protection against future regulatory compliance costs. The uncertainty regarding future fuel prices, carbon pricing mechanisms, and environmental regulations complicates economic analysis and favors propulsion system configurations that offer operational flexibility.

9. RESULTS AND DISCUSSION

9.1 Comparative Performance Analysis

The comparative analysis of marine diesel engine types reveals distinct performance envelopes that align with specific vessel applications. Low-speed two-stroke engines demonstrate superior thermal efficiency, with SFOC values 15–20% lower than medium-speed engines and 25–35% lower than high-speed engines at equivalent loads. This efficiency advantage translates directly to fuel cost savings that typically justify the higher capital cost and larger machinery space requirements of low-speed engines for vessels with high power demands and extensive operating hours.

The analysis of emission characteristics shows that all engine types can achieve compliance with current IMO regulations through appropriate technology combinations. Low-speed engines achieve Tier II NOx compliance through in-cylinder measures including optimized injection timing and advanced turbocharging, while Tier III compliance in ECAs requires either SCR aftertreatment or operation on LNG in dual-fuel mode [67]. Medium-speed engines offer greater flexibility for emission control, as their four-stroke architecture facilitates EGR implementation and their smaller exhaust gas volumes simplify SCR system sizing. High-speed engines, while inherently producing higher NOx emissions per unit power due to their higher combustion temperatures, can achieve compliance through SCR systems sized for their relatively small exhaust flows.

The IMO 2020 sulfur cap has had a profound impact on the marine fuel landscape, with VLSFO emerging as the dominant compliance fuel for vessels without scrubber installations. The price spread between HFO and VLSFO has varied significantly based on crude oil prices and refining margins, affecting the economic viability of scrubber investments [68]. Scrubber installations have proven economically advantageous for vessels with high fuel consumption and long remaining service lives, with payback periods typically ranging from 1 to 3 years depending on fuel price differentials. Alternative fuels, particularly LNG, have gained market share in segments where bunker infrastructure exists and regulatory incentives support their adoption.

9.2 Technology Trends and Future Outlook

The marine diesel engine industry is undergoing a period of significant transformation driven by regulatory pressure for emission reduction and the emergence of alternative fuels. Electronic control systems continue to advance, with the latest engine generations featuring integrated control of fuel injection, exhaust valve timing, turbocharging, and cylinder lubrication to optimize performance in real-time based on operating conditions [69]. Artificial intelligence and machine learning algorithms are being integrated into engine management systems to predict maintenance needs, optimize operating parameters, and reduce fuel consumption through adaptive control strategies.

The development of carbon-free and carbon-neutral fuels represents the most significant long-term trend affecting marine engine technology. Ammonia and hydrogen are the leading candidates for zero-carbon fuels, with both MAN Energy Solutions and Wärtsilä actively developing engines capable of operating on these fuels [70]. Methanol offers a nearer-term alternative that is already commercially available, with several methanol-powered vessels in operation and growing interest from major shipping lines. The transition to alternative fuels will require substantial investments in fuel production infrastructure, bunkering facilities, and engine technology, with the pace of adoption influenced by regulatory requirements, fuel costs, and industry commitment to decarbonization.

Waste heat recovery systems represent another area of active development, with advanced thermodynamic cycles including organic Rankine cycles (ORC) and steam turbine systems being applied to capture energy from engine exhaust gases [71]. These systems can improve overall propulsion plant efficiency by 5–10%, contributing to compliance with the

Energy Efficiency Design Index (EEDI) requirements while reducing fuel consumption and CO2 emissions. The integration of waste heat recovery with alternative fuel systems presents opportunities for further efficiency gains as the industry moves toward decarbonized propulsion.

10. CONCLUSION

This review has examined the types of marine diesel engines and their applications in modern ships, providing a comprehensive analysis of the technical characteristics, performance attributes, and operational considerations that influence engine selection. The classification of marine diesel engines by operating speed—low-speed (< 300 rpm), medium-speed (300–1000 rpm), and high-speed (> 1000 rpm)—provides a framework for understanding the distinct advantages and limitations of each engine category. Low-speed two-stroke crosshead engines deliver the highest thermal efficiency, exceeding 55% in the most advanced designs, and dominate the propulsion of large commercial vessels including tankers, bulk carriers, and container ships. Medium-speed four-stroke engines offer versatility for ferries, cruise ships, offshore vessels, and applications requiring operational flexibility. High-speed engines serve the lower end of the power spectrum with compact dimensions and rapid response characteristics.

The regulatory landscape, particularly IMO MARPOL Annex VI, has fundamentally shaped marine engine technology development in recent decades. The tiered NOx emission limits have driven the implementation of SCR systems, EGR technology, and dual-fuel engines capable of operating on natural gas. The IMO 2020 sulfur cap has accelerated the adoption of exhaust gas cleaning systems and alternative fuels. Looking forward, the industry's commitment to decarbonization will continue to drive innovation in engine efficiency, alternative fuel compatibility, and emission control technologies.

The selection of an appropriate marine diesel engine requires careful consideration of vessel type, operational profile, fuel availability, regulatory requirements, and lifecycle economics. As the maritime industry navigates the transition toward lower-carbon operations, the flexibility to adapt to changing fuel availability and regulatory requirements will become an increasingly important criterion in engine selection decisions. The continued development of dual-fuel and multi-fuel engine technologies, combined with advances in electronic control and waste heat recovery, positions the marine diesel engine to remain the dominant propulsion technology for commercial shipping in the coming decades, even as the fuels they burn evolve toward carbon-free alternatives.

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