ISSN: 2688-8645

A Review on the Current Status and Future Trends of Energy-Saving Technologies for Marine Diesel Engines

Yongkang Fu

School of Navigation and Shipping, Shandong Jiaotong University, Weihai Shandong, 264209, China

Abstract

Driven by tightening decarbonization requirements in international shipping and persistent pressure on total cost of ownership, improving the efficiency of marine diesel engines remains a near- to mid-term cornerstone for fuel and greenhouse-gas reduction. This review summarizes the regulatory drivers and energy-efficiency metrics, discusses the underlying loss mechanisms in marine diesel engines, and provides an expanded overview of major energy-saving technology pathways, including combustion and injection optimization, advanced turbocharging and air handling, Miller-cycle-based cycle improvement, waste-heat recovery and turbocompounding, friction and auxiliary-power reduction, and digital energy-efficiency management. Typical retrofit routes under EEXI/CII compliance, engineering constraints (backpressure, off-design behavior, reliability, maintenance), and techno-economic considerations are highlighted. Finally, the paper outlines development trends toward fuel-flexible engine platforms, low-load efficiency enhancement, modularized WHR solutions, hybridization, and well-to-wake/life-cycle-based assessment frameworks, offering references for both academic research and practical engineering implementation.

Keywords

Marine Diesel Engine; Energy Saving; Waste Heat Recovery; Miller Cycle; Turbocompounding; Dual-fuel; EEXI; CII; Life-cycle Assessment.

1. Introduction

Maritime transport underpins global trade, accounting for over 80% of the world's merchandise trade by volume, and is thus under increasing scrutiny due to its substantial energy consumption and greenhouse-gas (GHG) emissions—contributing around 3% of global anthropogenic CO_2 emissions. While alternative fuels (such as green methanol, ammonia, and hydrogen) and novel propulsion solutions (including fuel cells and hybrid systems) are emerging as long-term decarbonization pathways, internal-combustion-based prime movers—especially large two-stroke low-speed engines, which power the majority of deep-sea merchant vessels—are expected to remain dominant during the considerable transition period ahead. This is primarily due to their mature technology, reliable operation, and existing industrial supply chain. Accordingly, efficiency improvements at both the engine component level and the integrated ship-system level provide immediate, cost-effective, and scalable mitigation benefits to curb current emissions[1].

From an energy-flow perspective, only a fraction (typically 35%-45%) of the chemical energy stored in marine fuel is converted into useful shaft power to drive the propeller. The remainder is irreversibly rejected through various loss pathways: exhaust enthalpy (accounting for 40%-50% of total fuel energy), heat losses to cooling systems (25%-30%), mechanical friction between moving components, and pumping work associated with the engine's gas exchange process. The core engineering challenge is therefore not merely to raise the peak indicated

ISSN: 2688-8645

efficiency under ideal test conditions, but to deliver verifiable net fuel savings under real-world voyage scenarios—characterized by varying load profiles (from slow steaming to full power), unpredictable weather disturbances (wind, waves, and currents), dynamic maintenance states (such as component wear and fouling), and stringent regulatory compliance constraints (e.g., NOx Tier III and carbon intensity requirements)[2-4].

2. Regulatory Drivers and Energy-Efficiency Metrics

In the global context of maritime decarbonization, regulatory frameworks have profoundly reshaped the development and deployment direction of energy-saving technologies for marine diesel engines, marking a fundamental shift in optimization targets from "best test-bed efficiency" (pursuing maximum efficiency under ideal laboratory or bench test conditions) to "verifiable in-service performance" (ensuring stable and measurable energy-saving effects in real-world navigation scenarios). This shift has tightly coupled technical energy-saving measures (such as engine structure optimization, waste heat recovery systems) and operational optimization strategies (such as speed management, route planning) with mandatory monitoring, reporting, and verification (MRV) mechanisms[5, 6]. As a result, data quality (including accuracy, completeness, and real-time performance) and scientific assessment methodologies have become integral components of energy-saving technology deployment—only technologies with reliable data support and verifiable performance can meet regulatory requirements and gain market acceptance.

2.1. International Decarbonization Strategy and Regulatory Framework

Regulatory instruments have progressed toward a structured framework that combines targets, quantified indices, and data-backed compliance. Short-term measures focus on improving both technical and operational efficiency of existing ships, while mid-term measures are expected to introduce stronger economic incentives and broader greenhouse-gas accounting beyond CO_2 alone.

For engine and retrofit stakeholders, this implies that energy-saving technologies must be measurable, auditable, and sustainable in operation. A technology that shows a few-percent benefit during sea trials may deliver less in the long run if fouling, control limitations, or maintenance burdens erode performance[7].

Different instruments also bias technology choice. Technical indices tend to favor design-level improvements (propulsion matching, WHR, quantified power limitation), whereas operational indices highlight voyage optimization, speed management, and digital performance monitoring.

2.2. Energy-Efficiency Indicators and Assessment Boundaries

Energy-efficiency metrics for marine diesel engines and their supporting systems can be systematically categorized into three mutually complementary levels, each tailored to distinct assessment objectives and application scenarios. Engine-level indicators, which focus on the core energy conversion performance of the diesel engine itself, serve as the foundation for technical optimization and component-level performance evaluation. Key indicators in this category include Brake Specific Fuel Consumption (BSFC), a direct measure of fuel economy defined as the mass of fuel consumed per unit of brake power output (typically expressed in g/kWh), which directly reflects the efficiency of converting fuel chemical energy into mechanical work; Brake Thermal Efficiency (BTE)[6, 8], the ratio of the engine’s brake work to the total thermal energy released by fuel combustion, which quantifies the fundamental energy conversion efficiency of the engine’s thermodynamic cycle; and pumping loss proxies, such as the pressure difference between the intake and exhaust manifolds or the integral of in-cylinder pressure during the gas exchange process, which characterize the energy losses incurred by the

ISSN: 2688-8645

engine in drawing in fresh air and expelling exhaust gas—losses that become particularly significant under low-load operating conditions like slow steaming.

System-level indicators expand the assessment scope beyond the engine itself to the entire propulsion and shipboard energy supply system, emphasizing the synergistic efficiency of interconnected components. Representative indicators here include propulsion chain efficiency, a comprehensive metric that integrates the efficiency of the main engine, transmission system (such as clutches and gearboxes), propeller, and the hydrodynamic interaction between the propeller and the hull—this indicator is critical for evaluating the overall energy utilization efficiency of the ship's propulsion system, as inefficiencies in any single link (e.g., propeller fouling or poor engine-propeller matching) can significantly degrade the system's total performance[9]. Auxiliary load share refers to the proportion of electrical or thermal energy consumed by auxiliary equipment (such as pumps, fans, compressors, and boilers) in the ship's total energy consumption; for many merchant ships operating under part-load conditions, auxiliary loads account for 10%–20% of total energy use, making this indicator a key focus for operational energy-saving optimization. Net electrical balance, meanwhile, assesses the equilibrium between the electrical power generated by on-board sources (including main engine shaft generators, auxiliary diesel generators, and waste heat recovery power systems) and the total electrical demand of the ship, providing a basis for optimizing power generation scheduling and reducing redundant energy consumption[10, 11].

2.3. Methodological Evolution: From Steady-State Tests to Full-Profile, Life-Cycle Evaluation

Traditional energy-efficiency assessment of marine diesel engines relies heavily on steady-state bench tests, which typically only sample a limited set of fixed operating points (e.g., rated load, 75% load, 50% load). This approach has obvious limitations, as it fails to accurately represent the actual operating conditions of ships—such as long-term slow steaming (low-load, constant-speed operation), frequent load transients (acceleration, deceleration during berthing or navigation), and environmental disturbances (wind, waves, and currents that affect hull resistance and engine load). To address this mismatch, recent academic studies and industrial practices have increasingly advocated for load-profile-weighted evaluation methods. These methods base assessments on the actual load distribution of ships over representative shipping routes, and explicitly constrain safety margins for adverse sea conditions (e.g., strong winds, heavy waves) to ensure that the evaluated energy-saving effects are reliable and applicable in real maritime operations.

With the widespread popularization of onboard high-frequency sensors and the rapid development of cloud analytics technology, the paradigm of energy-efficiency assessment is gradually shifting toward hybrid approaches. These approaches integrate physics-based models (including engine cycle models, turbocharger matching models, and system energy balance models) with data-driven baselines (built through regression analysis, machine learning algorithms, etc.). The physics-based models ensure the interpretability of the assessment process by relying on fundamental thermodynamic and mechanical principles, while the data-driven baselines leverage massive real operational data to improve the accuracy of efficiency prediction. This hybrid framework not only enhances robustness against missing or abnormal onboard data but also provides clear logical support for regulatory auditing, which is highly aligned with the requirements of Monitoring, Reporting, and Verification (MRV) oriented regulations[12].

3. Loss Mechanisms and Energy-Saving Potential of Marine Diesel Engines

In the context of maritime decarbonization, understanding the distribution of energy losses in marine diesel engines—and identifying which losses are practically recoverable—is a

ISSN: 2688-8645

fundamental prerequisite for selecting effective energy-saving technologies. Beyond traditional first-law energy balances (focused on energy quantity conservation), exergy-based reasoning (evaluating energy quality and availability) plays a key role in prioritizing high-value heat sources. This approach helps avoid misleading solutions that appear promising in terms of recovered power but deliver limited net ship-level fuel savings once integration penalties (such as increased exhaust backpressure) are fully accounted for.

3.1. Loss Breakdown and Recoverability

It is critical to recognize that the fraction of energy loss does not equate to its recoverable value. Exhaust heat, typically at 300–550°C, has significantly higher temperature and exergy content than jacket water (80–120°C), making it the primary target for waste heat recovery (WHR). In contrast, lower-grade heat sources (e.g., jacket water, charge-air cooler waste heat) often require specialized systems like Organic Rankine Cycles (ORC), heat pumps, or absorption chillers to convert into useful power or shipboard service heat (e.g., cargo heating, domestic hot water).

Heat recovery systems inevitably introduce integration penalties. Exhaust heat recovery may increase engine backpressure, elevating pumping losses and shifting the turbocharger's operating point away from its high-efficiency region[13]. Recovering heat from cooling systems, on the other hand, may alter component operating temperatures, affecting thermal corrosion and fatigue boundaries. Thus, net ship-level fuel savings—not the absolute power recovered—must be the core evaluation metric to ensure the technology delivers real-world benefits[13].

Given the high variability of marine operations (e.g., load changes, route-dependent sea conditions), off-design performance is critical for sustained energy savings. Measures such as dynamic control of working-fluid flow in ORC systems, exhaust bypass strategies for WHR, and multi-source heat coupling (combining exhaust and jacket water heat) are necessary to maintain stable annual-average benefits across diverse operating scenarios.

3.2. Differences Between Low-Speed Two-Stroke and Medium-Speed Four-Stroke Engines

Low-speed two-stroke engines, the main propulsion choice for deep-sea merchant vessels (e.g., ultra-large container ships, bulk carriers), typically operate in a stable, narrow load range during long voyages and already achieve high peak thermal efficiency (up to 50%). Their energy-saving potential is therefore often unlocked through system-level technology stacking—such as combining exhaust gas boilers with steam turbines or power turbines for additional power generation—and optimizing engine-propeller matching to reduce hydrodynamic losses.

In contrast, medium-speed four-stroke engines (commonly used in coastal ships, ro-ro vessels, and as auxiliary generators) experience higher fractions of part-load and transient operation in many applications. For these engines, flexible solutions like variable valve actuation (VVA) strategies, advanced turbocharging systems (e.g., variable-geometry turbines, electric turbo-assist), auxiliary electrification, and control-oriented optimizations tend to deliver more stable savings than large-scale steam bottoming cycles, especially in retrofit scenarios.

Key constraints also differ between the two engine types: low-speed two-stroke engines are highly sensitive to scavenging efficiency and exhaust backpressure (excessive backpressure can severely degrade combustion and power output), while medium-speed four-stroke engines are often limited by transient smoke emissions and combustion stability when operating with high exhaust gas recirculation (EGR) rates or deep Miller cycle settings[14].

3.3. Part-Load and Transient 'Pain Points'

Slow steaming, a prevalent energy-saving operational strategy (operating at 20–50% rated load), pushes engines into low-load regions where turbocharger efficiency drops sharply,

ISSN: 2688-8645

scavenging deteriorates, and combustion temperatures decrease. This not only increases brake specific fuel consumption (BSFC) but also raises risks such as cold corrosion (caused by sulfuric acid condensation due to low exhaust temperatures). Consequently, the optimization focus shifts toward improving low-load efficiency while maintaining safe thermal conditions (e.g., optimizing injection timing, enhancing turbocharger low-load performance).

Transient operating conditions (e.g., acceleration, sudden load changes) pose another challenge: mismatches among fuel injection, boost pressure, and air-fuel ratio can lead to unstable combustion, increased smoke emissions, and even component damage. Energy-saving devices lacking fast-response control systems—such as WHR systems without rapid bypass or working-fluid flow control—may suffer large efficiency fluctuations or protective shutdowns during transients, eroding long-term energy gains.

Accordingly, a ‘control-first’ engineering philosophy is increasingly adopted in energy-saving retrofit design: first define controllable variables, required sensors, diagnostic algorithms, and protection logic upfront, then validate the system progressively through simulation, bench tests, sea trials, and long-term in-service monitoring to ensure reliability and stable performance across all operating conditions.

4. Current Status of Energy-Saving Technologies for Marine Diesel Engines

Energy-saving technologies for marine diesel engines cover a comprehensive range from in-cylinder process optimization (the core of energy conversion) to system-level energy recovery and digital operational management, forming a multi-dimensional technical system that runs through the entire energy flow of the engine and ship. In practical applications, the most valuable energy-saving solutions are usually those with robust off-design performance (able to maintain efficiency under variable load and speed conditions common in marine operations), predictable maintenance requirements (reducing the uncertainty of operational costs), and strong compatibility with existing engine-room layouts and ship electrical architectures (lowering retrofit difficulty and investment risks)[15, 16].

These characteristics ensure that the technologies can not only achieve significant fuel savings but also adapt to the complex and variable marine operating environment, gaining wide acceptance from ship operators.

4.1. Combustion and Fuel-Injection Optimization

Combustion optimization, as the core of in-cylinder energy-saving, aims to precisely adjust the phasing of in-cylinder heat release under the premise of ensuring engine reliability, thereby minimizing incomplete combustion (which wastes fuel and increases emissions) and excessive heat transfer (which reduces thermal efficiency). Modern electronic fuel injection systems have become the key support for this optimization, as they enable flexible control over injection timing, fuel injection rate shaping (such as ramp-up, plateau, and post-injection), and multi-pulse injection strategies—these capabilities provide a practical and cost-effective path for incremental energy savings, as they can often be achieved through software-upgradable calibration without extensive hardware modifications. On the hardware front, advancements such as higher injection pressure (which enhances fuel atomization fineness) and refined nozzle geometry (which optimizes fuel spray characteristics) further improve air-fuel mixing uniformity, directly boosting combustion efficiency; however, these upgrades may also increase fuel pump workload and accelerate component wear, requiring a balanced trade-off between energy-saving benefits and hardware durability during design[17].

Additionally, calibration processes must fully account for the variability of marine fuel properties, including viscosity, aromatic content, and the proportion of biofuel blends, to avoid operational issues such as wall wetting (which can lead to increased emissions and lubricant dilution), carbon deposits on combustion chambers (which affect heat transfer and compression ratio), and degradation of lubricant performance.

4.2. Advanced Turbocharging and Air Handling

Air handling systems serve as a critical link between in-cylinder combustion processes and the engine's external operating conditions, with the primary goal of delivering the optimal air-fuel mixture across the entire load range to ensure efficient and stable combustion. A major engineering challenge in this area is maintaining high turbocharging efficiency and acceptable transient response (e.g., rapid acceleration or load changes) when the engine operates at low loads, where fixed-geometry turbines often suffer from poor performance due to mismatched exhaust gas energy (insufficient energy to drive the turbine to generate required boost pressure)[18, 19]. To address this limitation, a range of advanced turbocharging technologies have been developed and applied, including variable-geometry turbines (which adjust the flow area of the turbine nozzle to match different load conditions, improving efficiency at both high and low loads), bypass systems (which redirect excess exhaust gas to avoid turbocharger overspeed and reduce backpressure), sequential turbocharging (using multiple turbochargers that activate sequentially based on load—small turbochargers for low loads and large ones for high loads), and two-stage boosting (employing two turbochargers in series to achieve higher pressure ratios).

Two-stage boosting, in particular, enables the implementation of deep Miller cycle strategies and significant NOx reduction by providing sufficient air pressure to compensate for the reduced trapped air mass associated with the Miller cycle; however, it also increases system complexity (more components and pipelines) and imposes higher maintenance demands. Electrified boosting solutions, such as electric turbo-assist (adding an electric motor to assist the turbocharger at low loads) or fully electric turbochargers (e-turbos), offer additional degrees of freedom by decoupling boost pressure control from exhaust energy recovery—this allows for more precise air management and improved transient response, especially in low-load scenarios. Nevertheless, electrified boosting requires compatibility with the ship's existing electrical architecture, integration of high-power density power electronics, and seamless coordination with the ship's energy management system to ensure optimal overall performance and avoid electrical system overload.

4.3. Cycle Improvement via Miller Strategies and High Boost

Miller cycle strategies represent a key approach to optimizing the engine's thermodynamic cycle, primarily by altering the effective compression process through either early intake valve closing (EIVC) or late intake valve closing (LIVC). This modification reduces the end-of-compression temperature while maintaining the expansion ratio (ensuring sufficient work output), which not only lowers NOx formation (by suppressing high-temperature combustion reactions) but also potentially reduces heat transfer losses from the cylinder to the cooling system (due to lower in-cylinder temperatures)[20, 21].

However, the trade-off is a reduction in trapped air mass (resulting from shortened intake time), which typically requires higher boost pressure (provided by advanced turbocharging systems) to maintain the required power output. The implementation of Miller cycle strategies varies significantly between engine types: four-stroke engines can leverage variable valve actuation (VVA) systems to achieve flexible scheduling of EIVC and LIVC, allowing the engine to adapt the cycle to different load and speed conditions (e.g., using LIVC at low loads for better stability and EIVC at high loads for higher efficiency); in contrast, two-stroke engines have more limited valve flexibility (usually relying on fixed camshafts), often requiring tailored cam profiles and precise turbocharger matching to implement the Miller cycle, making retrofit applications more challenging and costly. Several critical engineering constraints must be considered when adopting Miller strategies, including peak cylinder pressure and pressure-rise rate (to avoid mechanical damage to pistons, connecting rods, and cylinder heads), smoke emissions and combustion stability at low loads (especially when combined with EGR, which further reduces oxygen concentration), and thermal and corrosion boundaries of engine components (due to changes in in-cylinder temperature distribution)[22, 23].

As a result, Miller cycle strategies should never be evaluated as isolated modifications; instead, they must be integrated into a comprehensive calibration framework that co-optimizes injection parameters, boost pressure, and EGR rates to ensure balanced performance, emissions, and reliability.

5. Representative Engineering Applications and Retrofit Routes

For the existing ship fleet, the feasibility of retrofit is closely restricted by three core factors: dry-dock window availability, space and weight limitations, and system integration risks. Dry-dock resources are inherently scarce and require long-term scheduling, so any retrofit plan must be tightly aligned with the ship's fixed maintenance cycle to avoid unnecessary operational downtime. Meanwhile, the compact layout of traditional ship engine rooms leaves little room for new equipment installation, and the additional weight from retrofit components will directly affect the ship's draft, stability, and cargo capacity, requiring precise calculation and balance. Additionally, integrating new systems with the original power and control architecture carries risks of operational conflicts, which may endanger navigation safety if not properly addressed. Therefore, compliance-oriented retrofits generally adopt a phased implementation strategy: first, implement fast-to-deploy operational and soft measures that have minimal impact on the original system to quickly meet initial compliance requirements or reduce energy consumption, and then carry out hardware retrofits when the economic benefits are verified and the dry-dock window is available[24, 25].

5.1. EEXI-Oriented Retrofits: Power Limitation and Propulsion Optimization

As a core compliance target for the International Maritime Organization (IMO) to regulate the energy efficiency of existing ships, EEXI (Energy Efficiency Existing Ship Index) has driven the widespread adoption of targeted retrofit solutions. Among these, engine/shaft power limitation is recognized as a mainstream fast-track route due to its low investment, short implementation cycle, and simple modification process. Its energy-saving and compliance principle lies in limiting the maximum output power of the engine or propeller shaft through electronic control calibration or mechanical limiters, thereby forcing the ship to operate at a more economical load point, which typically reduces fuel consumption by 5%-8%[26]. However, this measure requires full assessment of safety margins under adverse sea conditions—such as strong winds, heavy waves, or ice navigation—to ensure the ship retains sufficient power reserve for emergency responses. Corresponding authorized override procedures must also be established, allowing the crew to temporarily lift the power limit in critical scenarios like maritime rescue, while implementing strict monitoring and recording mechanisms to prevent abuse[27].

Propulsion system retrofits, including propeller upgrade, installation of energy-saving ducts, fins, and rudder bulbs, are widely applied due to their favorable cost-per-percent-saving ratio. Propeller upgrade optimizes blade shape and pitch ratio based on the ship's actual operating profile to improve open-water efficiency and reduce cavitation losses. Energy-saving ducts and fins optimize the flow field around the propeller, reducing rotational energy loss of the water flow and enhancing thrust, while rudder bulbs recover partial wake energy to reduce hull resistance. On the engine side, derating (reducing maximum continuous output power) and turbocharger matching are essential supporting measures. These prevent long-term low-load operation, which can lead to incomplete combustion, carbon deposition, and accelerated component wear, thereby safeguarding engine efficiency and reliability.

ISSN: 2688-8645

5.2. Engineering WHR: From Newbuild Integrated Systems to Retrofit-Friendly Solutions

Waste Heat Recovery (WHR) technology is an effective way to improve ship energy efficiency by recovering waste heat from engine exhaust, jacket water, and intercoolers for power generation or heating. For newbuild vessels, WHR systems can be integrated into the overall design at the initial stage, achieving optimal thermal matching (coordinating engine and WHR operating parameters), rational layout (shortening heat transfer pipelines to reduce losses), and seamless electrical architecture integration (connecting waste heat power generation to the main grid). This integrated design maximizes waste heat recovery efficiency, typically reaching 10%-15%[28].

For existing ships, retrofit of WHR systems faces significant space and installation constraints. Thus, modular skid-based solutions—integrating heat exchangers, ORC (Organic Rankine Cycle) units, power turbines, and control systems into prefabricated skids—have become the mainstream choice. These skids can be pre-assembled and debugged in factories, significantly reducing on-board installation and commissioning time during dry-dock. Reliability and maintainability are critical for long-term benefits: fouling (from exhaust impurities) and corrosion (from seawater and exhaust components) reduce heat transfer efficiency and increase engine backpressure, directly eroding energy-saving gains. Therefore, life-cycle assessments must explicitly include cleaning strategies (e.g., online high-pressure water jet cleaning), corrosion-resistant material selection for key components, bypass/protection logic (to ensure engine normal operation when WHR fails), and maintenance planning to minimize downtime impact[29].

5.3. Dual-Fuel and Energy Saving: Efficiency, Methane Slip and Life-Cycle Perspective

Dual-fuel ships (primarily LNG-fueled) are a key transitional solution for shipping decarbonization, but it is important to distinguish between decarbonization and energy saving: decarbonization focuses on reducing carbon intensity per unit transportation, while energy saving targets total energy consumption. LNG's lower carbon content reduces tank-to-wake CO_2 emissions by approximately 25% compared to heavy fuel oil, but methane slip—unburned methane escaping during combustion—offsets these benefits. Methane's global warming potential (GWP) is about 28 times that of CO_2 over 100 years, so excessive slip can increase the well-to-wake climate impact (considering the full fuel life cycle from extraction to combustion).

The combustion concept of dual-fuel engines—low-pressure Otto cycle vs. high-pressure direct injection—significantly influences efficiency and emissions. Low-pressure systems have simpler structures but higher methane slip, while high-pressure systems achieve more complete combustion but higher manufacturing costs. Dual-fuel operation imposes stricter requirements on injection systems, turbocharger matching, and control systems to ensure stable combustion and rapid response across fuel modes. Vendor solutions focus on balancing methane slip reduction and efficiency retention, with actual benefits depending on the ship's route load profile (e.g., long-haul vs. short-sea) and LNG supply availability.

A prominent industry trend is upgrading diesel-engine platforms to accommodate methanol, ammonia, and drop-in bio/synthetic fuels, aligning with long-term zero-carbon goals. This upgrade direction makes fuel compatibility (adapting the engine and supply system to new fuel properties), supply-system energy efficiency (minimizing energy consumption for fuel storage and delivery), and safety (addressing the flammability, toxicity, or corrosiveness of alternative fuels) core topics for future research and retrofit design[30].

6. Future Trends and Research Hotspots

The clear orientation of the technology roadmap has also driven the coordinated transformation of the entire industrial chain in the shipbuilding industry. For engine manufacturers, it is necessary to lay out the research and development of standardized core components for multi-fuel platforms in advance to reduce the modification costs for adapting to different fuels. For shipping enterprises, it is necessary to select the appropriate energy recovery and hybrid power combination solution under the guidance of the technical roadmap, in light of the actual demands such as their own operating routes (near-sea/ocean-sea) and load characteristics. For the supply chain end, material enterprises need to accelerate the research and development of special materials that are resistant to corrosion and high temperatures, while electronic enterprises should strengthen the industrial application of intelligent control and digital twin technologies. At the same time, industry collaboration also needs to bridge the gap between technological research and development and policy regulation. By participating in the formulation and improvement of the "from well to propeller" accounting standards, it can promote the unification of the technology value assessment system, ultimately achieving a closed loop from planning to implementation of the technology roadmap, and providing sustainable power support for the low-carbon transformation of the global shipping industry.

6.1. Fuel Flexible Transformation and Precise Optimization of Efficiency Across All Operating Conditions

The current research and development of Marine engines is undergoing a critical shift, with the core being the construction of a multi-fuel flexible platform that is compatible with liquefied natural gas (LNG), methanol, ammonia, and various biological/synthetic fuels. This transformation needs to be achieved through the improvement of injection systems, the reconstruction of combustion structures, the application of special materials, and the upgrading of intelligent control strategies. The optimization objective has also shifted from the peak efficiency of a single fuel to a robust multi-objective optimal solution that addresses the uncertainties of fuel supply and the dynamic changes in emission regulations. The flexibility of fuel also brings new technical boundary challenges, including the differences in ignition characteristics of different fuels, flame stability control, the corrosion and lubrication effects of fuel on components, as well as energy loss and safety control of storage and supply systems and other key issues, driving the research focus to extend from the improvement of single-cylinder efficiency to the coordinated optimization of the entire system of "fuel - engine - ship". Meanwhile, with the increasing prevalence of low-speed navigation and port standby conditions, the efficiency of low-load operation has become a core indicator for measuring the competitiveness of engines. It is required that engines maintain excellent fuel consumption rate (BSFC) and emission stability in the low-load range and achieve a safe and rapid response switch to high-load conditions. Therefore, turbine matching optimization, valve control strategy innovation, thermal management system upgrade and control-oriented optimization will continue to be research hotspots. Combined with in-flight data-driven continuous calibration technology, the reliability and economy of all-condition operation will be further consolidated.References[13, 21, 30].

6.2. Integrated Energy Recovery and Coordinated Upgrade of Hybrid Power Systems

In the future, ship energy recovery (WHR) technology will develop in depth towards integration and modularization. The trend of integration is reflected in the precise coupling and matching of multiple heat sources such as exhaust gas waste heat, pressurized air cooling waste heat, and cylinder liner cooling water waste heat with the power and heat demands of ships. The modular design enables rapid installation during dry-docking through standardized interfaces,

ISSN: 2688-8645

providing core support for the retrofit upgrade of the existing fleet. In terms of technical paths, the steam-Rankine cycle, the organic Rankine cycle (ORC), and the carbon dioxide cycle will form a complementary and coexisting pattern: The steam cycle is suitable for high-grade waste heat recovery, the ORC system focuses on the utilization of medium and low-grade multi-source waste heat, and the carbon dioxide cycle, with its compactness advantage, is expected to achieve large-scale application after the improvement of technological maturity and cost reduction. The level of variable working condition control will directly determine the annual energy-saving benefits in actual operation. Developing in tandem with energy recovery technology is the hybrid propulsion system, which, through the flexible configuration of motors, batteries and energy storage devices, stabilizes the load fluctuations of the main engine and ensures that the prime mover always operates within the high-efficiency range. This type of system is particularly effective in energy conservation for ships with frequent load changes, while ocean-going vessels are more suitable for adopting the combined scheme of "power output/input (PTO/PTI) + energy recovery". Current research has focused on the optimal energy management strategy under multiple constraints, comprehensively considering factors such as battery degradation rate, fluctuations in fuel and carbon prices, and maintenance costs. The introduction of digital twin technology provides strong support for predictive optimization.

6.3. Evaluation System Upgrade: From Single CO_2 to Full Life Cycle Full Greenhouse Gas Accounting

As the environmental impacts of non-carbon dioxide greenhouse gases such as methane and nitrous oxide have drawn widespread attention, assessment indicators centered solely on carbon dioxide can no longer accurately measure the superiority or inferiority of technologies, and may even lead to deviations in technology ranking. Against this backdrop, the "Well-to-Wake (WTW)" accounting system from a full life cycle perspective, methane escape sensitivity analysis, and quantification of emission uncertainty intervals will gradually become standard components of ship power technology assessment. This upgrade requires that future research must break through the limitations of traditional single numerical estimation, clearly define the system boundary range, clarify the data sources of emission factors, and publicly present the confidence intervals of emission results. Through a transparent and all-round assessment framework, it provides a scientific basis for the selection and iteration of low-carbon ship technologies.

References

[1] Altosole, M., et al., A Diesel Engine Modelling Approach for Ship Propulsion Real-Time Simulators. Journal of Marine Science and Engineering, 2019.

[2] Balan, K.N., et al., Investigation on emission characteristics of alcohol biodiesel blended diesel engine. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 2018.

[3] Bogdanowicz, A. and T. Kniaziewicz, arine Diesel Engine Exhaust Emissions Measured in Ship's Dynamic Operating Conditions. Sensors, 2020.

[4] Choi, B., K. Lee, and G. Son, Review of Recent After-Treatment Technologies for De-NOx Process in Diesel Engines. International Journal of Automotive Technology, 2020.

[5] Crump, K.S., C. Van Landingham, and R.O. McClellan, Influence of Alternative Exposure Estimates in the Diesel Exhaust Miners Study: Diesel Exhaust and Lung Cancer. Risk Analysis, 2016.

[6] Dere, C. and C. Deniz, Load optimization of central cooling system pumps of a container ship for the slow steaming conditions to enhance the energy efficiency. Journal of Cleaner Production, 2019.

[7] Dong, X., Analysis and Research on Energy Saving and Emission Reduction of Ships. IOP Conference Series: Earth and Environmental Science, 2020.

[8] Feng, Y., et al., A Zero-Dimensional Mixing Controlled Combustion Model for Real Time Performance Simulation of Marine Two-Stroke Diesel Engines. Energies, 2019.

ISSN: 2688-8645

[9] Geertsma, R.D., K. Visser, and R.R. Negenborn, Adaptive pitch control for ships with diesel mechanical and hybrid propulsion. Applied Energy, 2018.

[10] Hwang, S.-C. and H. Nam, Analysis of Retrofit SCR System for Small-Sized Ship Diesel Engines Using Numerical Methods. Korean Journal of Chemical Engineering, 2024.

[11] Jing, G.X., et al., Investigation into diesel engine cylinder head failure. Engineering Failure Analysis, 2018.

[12] Lamaris, V.T. and D.T. Hountalas, A general purpose diagnostic technique for marine diesel engines – Application on the main propulsion and auxiliary diesel units of a marine vessel. Energy Conversion and Management, 2010.

[13] Lebedevas, S. and T. Čepaitis, Complex Use of the Main Marine Diesel Engine High- and Low-Temperature Waste Heat in the Organic Rankine Cycle. Journal of Marine Science and Engineering, 2024.

[14] Lebedevas, S. and T. Čepaitis, Methodological Solutions for Predicting Energy Efficiency of Organic Rankine Cycle Waste Heat Recovery Systems Considering Technological Constraints. Journal of Marine Science and Engineering, 2024.

[15] Lee, H. and Y. Jeong, The effect of dynamic operating conditions on nano-particle emissions from a light-duty diesel engine applicable to prime and auxiliary machines on marine vessels. International Journal of Naval Architecture and Ocean Engineering, 2016.

[16] Lv, Y., et al., Investigation of biodiesel and its blends fueled diesel engine: An evaluation of the comprehensive performance of diesel engines. Renewable Energy, 2024.

[17] Muscat, J.E. and E.L. Wynder, Diesel exhaust, diesel fumes, and laryngeal cancer. Otolaryngology-Head and Neck Surgery, 2022.

[18] Pelić, V., et al., The Impact of Slow Steaming on Fuel Consumption and CO2 Emissions of a Container Ship. Journal of Marine Science and Engineering, 2023.

[19] Pino, J.S., et al., Analysis of cytotoxicity and genotoxicity of diesel exhaust PM2.5 generated from diesel and dual natural gas-diesel engines. Environmental Toxicology and Pharmacology, 2025.

[20] Reis, H., et al., Diesel exhaust exposure, its multi-system effects, and the effect of new technology diesel exhaust. Environment International, 2018.

[21] Sagin, S., et al., Ensuring Reliable and Safe Operation of Trunk Diesel Engines of Marine Transport Vessels. Journal of Marine Science and Engineering, 2022.

[22] Shi, J., et al., Energy-Saving and Pollution-Reduction Potential Analysis for Diesel Engines Fueled with Fischer–Tropsch Fuel. ACS Omega, 2021.

[23] Shi, Q. and Y. Hu, Review on Intelligent Diagnosis Technology of Electronically Controlled Fuel Injection System of ME Diesel Engine. Academic Journal of Science and Technology, 2022.

[24] Singh, N. and R. Kaushal, Optimization of Engine Parameters Using Taguchi Technique for a Diesel Engine Running on a Newly Developed bio-nano Diesel Emulsion. Arabian Journal for Science and Engineering, 2023.

[25] Tan, P.-q., et al., Modeling of soot fragmentation that proceeds in a catalyzed diesel particulate filter of a diesel engine. Chemical Engineering Journal, 2019.

[26] Wang, K., et al., Joint energy consumption optimization method for wing-diesel engine-powered hybrid ships towards a more energy-efficient shipping. Energy, 2022.

[27] Wardana, M.K.A. and O. Lim, Review of Improving the NOx Conversion Efficiency in Various Diesel Engines fitted with SCR System Technology. Catalysts, 2022.

[28] Xie, L. and J. Yang, Performance Modulation of S-CO2 Brayton Cycle for Marine Low-Speed Diesel Engine Flue Gas Waste Heat Recovery Based on MOGA. Entropy, 2022.

[29] Yang, J., L. Quan, and Y. Yang, Excavator energy-saving efficiency based on diesel engine cylinder deactivation technology. Chinese Journal of Mechanical Engineering, 2012.

[30] Zhang, S. and Z. Zhang, Research on the Field Dynamic Balance Technologies for Large Diesel Engine Crankshaft System. Shock and Vibration, 2017.