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A Review of Ship Energy Efficiency and Emission Reduction Technologies under the IMO's Decarbonization Framework

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Abstract

This paper presents a systematic review of ship energy efficiency improvement and emission reduction technologies. Framed within the regulatory framework established by the IMO namely EEDI, EEXI, and CII the study analyzes ship energy consumption structures, emission characteristics, and compliance requirements. From a technical pathway perspective, the paper focuses on energy efficiency improvement measures (including hull form optimization, lightweight materials, propulsion system enhancements, and renewable energy integration) as well as emission reduction strategies (such as exhaust gas after-treatment, alternative fuels, and intelligent operational management). The findings indicate that the synergistic integration of multiple technologies combined with intelligent optimization can significantly reduce ship carbon intensity. Looking ahead, technological breakthroughs in zero-carbon fuels, carbon capture, and digital twins are essential to advancing the shipping industry toward its carbon neutrality goals.

Keywords

Ship energy efficiency; emission control; energy-saving technologies; alternative fuels; intelligent operation.

1. Introduction

Against the backdrop of sustained global shipping industry expansion and mounting pressures from climate change, ship energy efficiency improvement and emission reduction technologies have become central to the green transformation of the maritime sector. The International Maritime Organization (IMO), through Annex VI of the MARPOL Convention, has progressively established a regulatory framework for ship energy efficiency covering the entire lifecycle of vessels: the Energy Efficiency Design Index (EEDI) sets CO_2 emission limits for newbuild ships; the Energy Efficiency Existing Ship Index (EEXI) requires existing vessels to meet specific energy efficiency standards through technical retrofits; and the Carbon Intensity Indicator (CII) mandates annual carbon intensity rating and mandatory year-on-year reduction for in-service ships. Collectively, these regulations constitute the institutional framework for compliance and green transition in the shipping industry.

Current research focuses on the analysis of ship energy consumption structures and emission characteristics, energy efficiency improvement technology pathways, and emission reduction strategies such as exhaust gas after-treatment and alternative fuels, aiming to achieve significant reductions in the carbon intensity of the shipping industry through multi-technology

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integration and intelligent management. Nevertheless, current research still faces challenges in terms of technological maturity, economic viability, and discrepancies in regulatory implementation across regions. These challenges need to be addressed through interdisciplinary collaborative innovation and policy-market mechanisms to support the sustainable development of the shipping industry under the "dual carbon" goals.

2. Ship Energy Consumption and Emission Analysis

2.1. Ship Energy Consumption

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The energy consumption of a ship during navigation can be divided into five major modules according to their functions: main propulsion system (40%-60%), auxiliary machinery (15%-30%), cargo handling (10%-20%), hotel load (5%-15%), and anchoring and maneuvering (3%-8%). Among these, the main engine, as the largest energy-consuming unit, has its energy conversion efficiency directly determining the overall energy consumption level of the vessel.

Taking a typical two-stroke low-speed diesel engine as an example, only about 44% of the fuel chemical energy is converted into effective power, while the remainder is largely dissipated as exhaust heat loss (over 40%) and cooling loss (approximately 9.4%) [1]. The energy conversion of auxiliary systems also exhibits significant losses: the total efficiency of generators is only 90%-92%, and the ship's cable network, which can extend for hundreds of kilometers, further exacerbates Joule heating losses [2-3]. Although the boiler system accounts for only 3% of energy consumption, its exhaust heat loss still exceeds 25% of the fuel energy, indicating substantial waste heat recovery potential [4].

The energy transfer chain of the propulsion system is even more complex. From the main engine output to propeller work, the energy passes through mechanical components such as the shafting, bearings, and reduction gears, resulting in cumulative mechanical losses of approximately 5%–8% [5]. When converting mechanical energy into thrust, the propeller's total propulsion efficiency is typically only about 72% due to fluid viscosity, cavitation effects, and hull–propeller interaction losses [6]. Exergy analysis of a 75,000 DWT tanker further reveals that the available energy efficiency of the entire thermodynamic system is merely 48.26%, with irreversibilities in the heat transfer process (i.e., heat transfer across finite temperature differences) being the primary cause of exergy destruction [7].

2.2. Ship Emission Analysis

Ship emissions mainly fall into two categories: air pollutants and greenhouse gases. Air pollutants include sulfur oxides (SO_x), nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO), and volatile organic compounds (VOCs); greenhouse gases mainly include carbon dioxide (CO_2), methane (CH_4), and hydrofluorocarbons (HFCs) [8-9]. Particulate matter is classified by particle size into PM2.5 and PM10, of which PM2.5 can penetrate deep into the alveoli, while PM10 deposits in the upper respiratory tract. SO_x is converted into sulfate secondary aerosols in the atmosphere, and NO_x, primarily emitted as NO and rapidly oxidized to NO_2, both of which are important precursors of air pollution [8].

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The spatiotemporal distribution of ship emissions exhibits significant variations across ship types and geographical regions. At Shanghai Yangshan Port, container ships account for 38% of total pollutant emissions, while oil tankers, general cargo ships, and passenger ships account for 21%, 19%, and 8%, respectively [10]. At Qingdao Port, the NO_x emission share of container ships is even higher, reaching 55.5%, with bulk carriers and oil tankers accounting for 12.9% and 12.5%, respectively [11]. In the Yangtze River basin, carbon emissions from cargo ships account for as high as 79.06% of the total [12]. On a global scale, the EU-reported shipping greenhouse gas emissions show that container ships account for 30%, while oil tankers and bulk carriers account for 15% and 12%, respectively [13].

See Fig. 1.

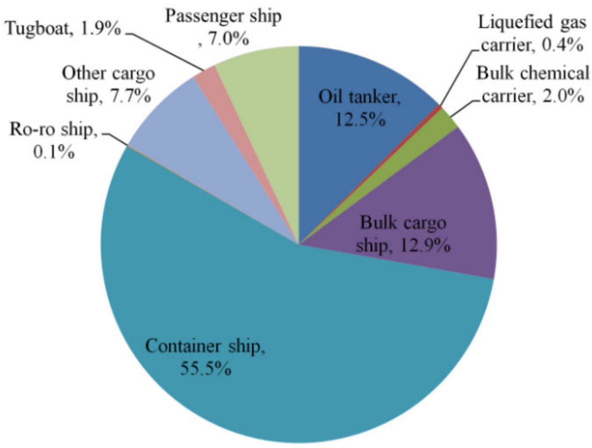

Figure 1. NO_x emission share by vessel type[11]

In response to the aforementioned emission characteristics, the IMO has established a multi-tiered emission control policy framework. Regarding SO_x control, the global fuel sulfur content limit has been reduced to 0.5% since 2020 (a significant decrease from 4.5% in 2000), while the five Emission Control Areas (ECAs), including the Baltic Sea and North America, have enforced a stringent 0.1% standard since 2015 [14–18]. In terms of NO_x tiered control, the Tier II limits (effective from 2011) range from 7.7 to 14.4 g/kWh, while Tier III (effective in ECAs from 2016) drastically drops to 2.0–3.4 g/kWh, representing a reduction of approximately 80% [19–20]. The Carbon Intensity Indicator (CII) rating system has been implemented since 2023, requiring ships to continuously improve their annual ratings through speed optimization and the Ship Energy Efficiency Management Plan (SEEMP III) [21].

3. New Energy and Hybrid Technology

In the technological pathways for improving ship energy efficiency, new energy and hybrid technologies have become the core direction for promoting the low-carbon transformation of the shipping industry by integrating renewable energy and clean energy. According to the review by He Yin et al., new energy ship power systems mainly cover four technological routes: solar energy, wind energy, fuel cells, and hybrid power [22]. Solar-powered ships use photovoltaic panels to convert electricity, combined with energy storage systems to smooth out fluctuations, but are limited by deck area and the corrosiveness of the marine environment [23]. Wind-powered ships achieve energy savings through Wind-Assisted Propulsion Systems (WASP); Vidović et al. pointed out that they can achieve significant fuel savings at various speeds [24]. Fuel cell ships adopt Proton Exchange Membrane Fuel Cell (PEMFC) technology,

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but hydrogen storage faces safety and cost challenges of high-pressure/liquid storage, requiring the establishment of standardized specifications [25-26].

Hybrid systems improve energy efficiency through topology optimization. Albers et al. proposed an automated topology synthesis method based on graph theory, combining mechanical propulsion with electric propulsion [27]. As a key energy storage unit, the increase in energy density and the decrease in cost of lithium batteries have promoted their application in ships. Kolodziejski et al. confirmed that hybrid systems can reduce fuel consumption by 25% and greenhouse gas emissions by 50%, with a payback period of approximately 5–8 years [28]. Research on hybrid energy storage systems (HESS) by Zhu Jiang shows that a lithium nickel cobalt manganate–lithium titanate battery combination can reduce costs by 28% and weight by 30% [29]. Hydrogen fuel cells have also achieved engineering breakthroughs in the maritime field; the Flagships project has realized fuel cell-driven cargo ships [30]. However, Dall'Armi et al. pointed out that their life-cycle cost is still higher than that of traditional systems, and energy efficiency needs to be optimized through heat recovery [31].

Table 1. see Table 1.

Table 1. Comparison of four new energy technology routes

Energy Type	Advantages	Disadvantages	Carbon Emissions
Solar	Abundant resources; quiet operation; low maintenance	intermittency dependent; no generation at night; low energy density	Near-zero in operation; emissions from manufacturing
Wind	Low cost; mature technology; high efficiency	Unstable; noisy; impact on birds	Near-zero in operation; emissions from construction
Fuel Cell	Long fast refueling; zero pollution endurance;	Limited infrastructure; high cost; difficult hydrogen storage	Zero in operation; depends entirely on hydrogen source
Hybrid Power	Significant fuel savings; no range anxiety; mature technology	Still uses fossil fuel; complex structure; still emits pollutants	Lower emissions; not zero-carbon

Economic analysis shows that although the ammonia-fuel hybrid system reduces carbon emissions by 66%, it increases life-cycle costs by 40%; solar hybrid systems can reduce operating costs by 19.6% in ferry applications [32-33]. Zhang et al. established a carbon intensity prediction model based on AIS–meteorological data collaboration, optimized with ANN and XGBoost algorithms to improve prediction accuracy [34]. IMO regulations continue to drive technological development; the EEDI Phase III standard requires new ships in 2025 to achieve a 30% improvement in energy efficiency compared to the baseline, making hybrid power a preferred solution for warships, tugboats, and other vessel types [35].

At the current stage, the application technologies of lithium-ion batteries and fuel cells as main power sources for pure electric or hybrid systems are becoming increasingly mature. Research focuses on the safe integration of high-energy-density energy storage systems, power dynamic allocation strategies for multi-energy hybrid systems, and the development of intelligent energy management algorithms based on operating conditions. Research and development of low-carbon fuel engines using methanol, ammonia, etc., and their supporting storage and supply technologies are active, aiming to overcome the range limitations of pure electric modes and achieve low-carbon operation throughout the life cycle [36]. Future technological pathways

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will exhibit diversified characteristics, with the core being to break through key technologies such as high-safety energy storage, low-cost green fuels, and intelligent energy efficiency control, and to accelerate technological iteration and industrialization through full-scale ship verification.

4. Ship Emission Reduction Technology Pathways

DPF can remove accumulated carbon through active or passive regeneration. OC (Oxidation Catalyst) reduces PM concentration by oxidizing soluble organic fractions (SOF) in exhaust gas over platinum/palladium catalysts, while simultaneously reducing HC and CO emissions. However, high-sulfur fuel can easily cause catalyst sulfur poisoning and deactivation, and sulfur-resistant catalysts are still in the research and development stage [37].

DPF physically intercepts particulate matter through inertial impaction, diffusion, and gravitational settling mechanisms. Ceramic or metal-based filter elements can achieve a PM removal efficiency of over 90%. Its core challenge lies in filter regeneration—sulfates generated from high-sulfur fuel combustion can clog pores, while ash accumulation exacerbates backpressure increase. Passive regeneration relies on NO_2 oxidation (requiring low-temperature conditions), and active regeneration requires an external heat source (approximately 600°C); neither can be stably achieved in the marine operating environment [37-39]. The DOC–DPF integrated device developed by Tang et al. verified a PM removal rate of over 90% for marine applications, but sulfate deposition caused by high-sulfur fuel may increase backpressure and regeneration frequency [40]. EGR reduces NOx formation by 15-30% through exhaust gas recirculation to lower in-cylinder oxygen concentration and combustion temperature. However, Kim et al. pointed out that when combined with SCR, it exacerbates particulate emissions and requires DPF to achieve coordinated pollutant control [41].

High integration has become a new trend in aftertreatment technology development. Schraml et al. proposed embedding SCR functionality into DPF to form an SDPF (SCR-coated DPF) component, reducing space occupation by 20-30% compared to traditional SCRT (SCR+DPF) systems, and resolving the competition between NO_2 in soot oxidation and fast SCR reactions through optimized catalyst distribution [41]. However, the passive regeneration capacity of this design is limited under low-load conditions and relies on high-load operating cycles to achieve safe regeneration. A retrofit case by MAN demonstrated that the SDPF system successfully met the CCNR Stage V emission standards on a cargo ship operating on the Danube River in Romania, but additional electric heating was required during cold start to maintain the catalyst temperature window [42].

5. Alternative Fuel Technologies

Alternative fuels have formed a diversified system centered on liquefied natural gas (LNG), ammonia, methanol, biofuels, and hydrogen. In their study, Wang and Wright explicitly defined alternative fuels as "any form of energy used for ship propulsion other than conventional fuel oil," covering LNG, liquefied biogas (LBG), biodiesel, methanol, ammonia, hydrogen, and electricity [43]. Among these, LNG has become the current mainstream choice due to its highest level of technological maturity. Owing to its high degree of commercialization, relatively complete industrial chain, and capability to significantly reduce sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter emissions, while offering approximately 20%–25% carbon dioxide reduction potential, it presents immediate feasibility as a compliance measure under the existing Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) frameworks, despite the issue of methane slip. Ellian et al. noted that dual-fuel engine designs can be compatible with existing marine propulsion systems, significantly reducing SOx and particulate emissions [44]. However, Li et al. emphasized that its application remains

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constrained by bottlenecks such as high initial investment costs, the encroachment of low-temperature tanks on cargo space, insufficient coverage of global bunkering infrastructure, and the lack of crew safety operation training systems [45]. Wurster et al. further confirmed that dual-fuel engines, with their fuel flexibility (natural gas proportion up to 99%), have become shipowners' preferred choice, whereas single-fuel engines, despite a 5%-8% efficiency improvement, require sacrificing operational flexibility [46].

Hydrogen fuel cell technology, with its zero-emission characteristics, has become a key pathway toward zero-carbon shipping. Wang et al. pointed out the intensive emergence of international demonstration projects, such as the sea trials of Ulstein's SX190 hydrogen-powered vessel, the delivery of Nedstack's MT-FCPP-100 marine fuel cell system, and the all-fuel-cell-driven ferry "Sea Change" [47]. Although hydrogen fuel possesses zero-carbon characteristics, it faces challenges related to cryogenic liquid hydrogen storage. In 2021, the China Classification Society (CCS) issued the first marine fuel cell product certificate to Zhongyu Power, marking a breakthrough in the technology certification system [48]. However, Van Hoecke et al. (2021) revealed that large-scale application still faces severe challenges from liquid hydrogen storage: under standard conditions, the volumetric energy density of hydrogen is only 8.4 MJ/m^3, requiring reliance on high-pressure (70 MPa) or cryogenic liquefaction (–253°C) technologies to improve storage efficiency, and the risk of hydrogen permeation in composite materials needs to be controlled through innovative designs such as "micro-leakage no-break" (μLNB) [49]. Thermal management system optimization also presents technical difficulties; a coupled control model based on Particle Swarm Optimization and Artificial Neural Network (PSO-ANN), by dynamically adjusting coolant flow and inlet temperature (with a set temperature difference not exceeding ±2°C), suppresses the stack temperature fluctuation within ±1.5% [50]. Although hydrogen possesses zero-carbon characteristics, it faces challenges such as cryogenic liquid hydrogen storage (–253°C), safety risks, and lack of infrastructure, necessitating international cooperation to promote the development of technical standards and supply chains. see . see Fig. 2.

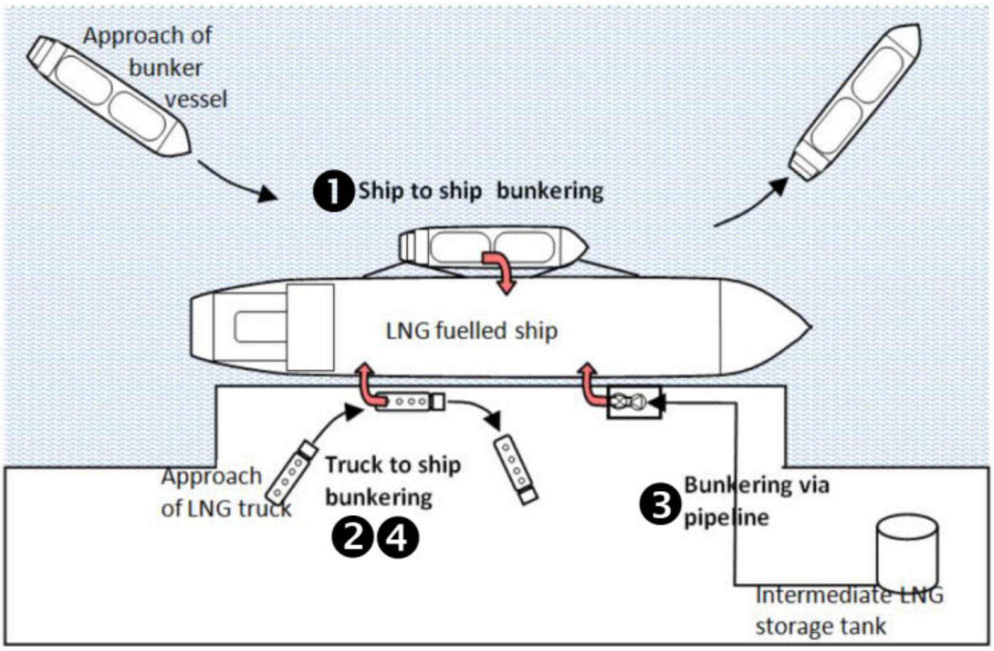

Figure 2. Retrofitting of LNG Fuel Tanks for Maritime Transport Vessels

Ammonia energy has become a research and development focus for engine manufacturers due to its relatively high energy density, mature storage and transportation technologies, and the

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potential to achieve full life-cycle carbon neutrality through synthesis using green hydrogen. However, its combustion characteristics and exhaust gas treatment pose technical barriers. Wang Jingzhou et al. (2024) emphasized that the nitrogen oxides (NO_x) concentration in its combustion products can reach 2–3 times that of conventional fuels, necessitating a two-stage catalytic reduction system-first using a vanadium-based catalyst (V_2O_5-WO_3/TiO_2) to achieve a 90% denitrification rate, followed by a copper molecular sieve (Cu-SSZ-13) to catalytically decompose the by-product N_2O [51].

Renewable fuels such as biomethane and bioethanol significantly reduce full life-cycle carbon emissions through feedstock diversification. Their core mechanism lies in utilizing non-food biomass, waste, and marginal land resources to replace traditional food crops, thereby reducing land-use change emissions and improving resource circulation efficiency. Bioethanol feedstocks encompass three categories: saccharine (sugarcane, sugar beet), starchy (corn, wheat), and cellulosic (straw, wood). Among these, sugarcane ethanol has a full life-cycle carbon emission of 59.18 g CO_2-eq/kWh, slightly lower than sugar beet ethanol (59.26 g CO_2-eq/kWh), while cellulosic ethanol can achieve further emission reductions through lignin deconstruction technology [52-53]. Biomethane primarily uses organic waste and agricultural residues as feedstocks, with a full life-cycle carbon emission intensity of only 5-15 g CO_2-eq/MJ, representing an 82%–94% reduction compared to fossil natural gas [54]. A comparative study by Wang et al. (2023) showed that biobutanol, with a vapor pressure (3 kPa) close to that of gasoline and an energy density (29.2 MJ/L) 49% higher than ethanol, is more suitable as a marine blending fuel [55].

Regulations from the International Maritime Organization (IMO) strongly drive technological transformation. Månsson (2017) pointed out that the global sulfur cap (sulfur content ≤ 0.5% from 2020) forces ships to choose low-sulfur fuels, scrubbers, or alternative fuels [56]. Zamboni et al. (2024), based on a full life-cycle (Well-to-Wake, WtW) Carbon Intensity Indicator (CII) assessment, found that green ammonia and green methanol can maintain a Class A energy efficiency rating for ships, while bio-LNG only reaches Class B due to upstream methane slip (escape rate > 3%) [57]. In typical shipyard practices, the 18,000 TEU container ships built by Hyundai Heavy Industries for United Arab Shipping Company (UASC) adopted an LNG-diesel dual-fuel system, while Mitsubishi Heavy Industries developed the UEC-LSGi high-pressure direct injection engine (pressure > 300 bar) to improve thermal efficiency [58]. Maersk's consecutive orders for methanol-powered container ships built by Hyundai Heavy Industries (to be delivered in 2025) highlight the trend of fuel diversification [59].

Marine alternative fuel technologies are following a development path of "short-term LNG transition, mid-term ammonia/hydrogen breakthrough, and long-term biofuel supplementation." Wang and Wright (2021) emphasized that balancing technological maturity and economic viability is crucial: although LNG can achieve rapid emission reductions, its carbon constraints are limited; hydrogen/ammonia need to overcome storage and transportation bottlenecks; and biofuels rely on sustainable feedstock certification [59]. Future technological iterations need to be combined with revisions to the IGF Code (International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels) and coordinated infrastructure construction, in order to achieve the IMO's strategic goal of reducing greenhouse gas emissions by 50% by 2050 [60].

6. Operational Optimization and Intelligent Technologies

Operational optimization and intelligent technologies significantly reduce fuel consumption and carbon emissions by integrating weather routing, speed coordination control, dynamic scheduling algorithms, and big-data-driven decision-making. The IMO energy efficiency framework (EEXI, CII, SEEMP) continuously drives technological iteration and shifts research

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attention toward multi-objective collaborative optimization. Zis et al. (2020) systematically summarized the classification system of weather routing technologies, noting that multi-objective optimization based on dynamic programming and genetic algorithms can comprehensively balance fuel efficiency, voyage time, and emission constraints; their study showed that route optimization considering wind and wave data can reduce fuel consumption by 12%-16% [60]. Yang et al. (2020) further introduced an ocean current dynamics model and verified that speed-current collaborative optimization can improve container ship energy efficiency by 8.3% while reducing carbon emissions by 23.29% [61]. Du Wei (2023) proposed a time-distance–meteorology coupling model and realized VLCC route–speed collaborative optimization through an improved fractional-order particle swarm algorithm; compared with traditional single-objective optimization, fuel consumption was further reduced by 0.82% and voyage time shortened by 3.73%, while the developed dynamic meteorological data loading technology effectively solved the sea-state matching problem [622].

The empowerment of operational optimization by intelligent technologies is reflected in real-time perception and decision-support. Li (2020) designed a ship energy consumption monitoring system integrating oval-gear flowmeters and GPS modules to enable dynamic correlation analysis between heavy fuel oil consumption and navigation parameters, providing a data foundation for optimization [63]. Wang Kai et al. (2023) pointed out that AI-based energy efficiency management systems can dynamically predict optimization space for speed and trim through navigation environment identification and energy-efficiency correlation analysis, but must break through the bottleneck of multi-source heterogeneous data fusion [64]. Yuan et al. (2023) proposed a speed–energy-allocation collaborative optimization method for hybrid ships, combining reinforcement learning algorithms to dynamically adjust diesel engine speed and battery charge/discharge strategies, improving the energy efficiency ratio by 5.19% [65]; Cai Xiaochi et al. (2024) adopted the SCE-UA algorithm to further optimize this indicator, achieving a 17% speed improvement over the genetic algorithm and effectively delaying CII rating downgrade [66].

Dynamic scheduling algorithms strengthen port coordination efficiency. Shao et al. (2024) combined Virtual Arrival and the NSGA-II algorithm to build a ship scheduling model; in a Ningbo-Zhoushan Port case, waiting time was reduced by 31.41% and carbon emissions by 23.29% [67]. Choi et al. (2023) used a quadtree-initialized path dynamic programming algorithm, embedding the time dimension into the navigation map to realize segmented speed optimization and verified a significant reduction in fuel consumption [68]. Digital twin technology promotes scheduling intelligence: Wang et al. (2024) established a ship workshop production twin and used a PSO-GA hybrid algorithm to optimize processing cycles, improving global convergence speed and stability [69].

IMO regulations continue to drive technological innovation. Miller et al. (2014) reviewed the constraints of the three-phase EEDI standards (2015/2020/2025) on technology roadmaps, noting that new ships in 2025 must improve energy efficiency by 30% [70]; Bašić et al. (2024) emphasized that EEXI and SEEMP promote deep integration of propeller optimization, wind-assisted propulsion, and renewable energy technologies [71]. Life-Cycle Performance Assessment (LCPA) models have become a new trend: Gualeni et al. (2018) integrated LCC and LCA to construct a ship breakdown structure, quantifying design–operation comprehensive energy efficiency through key performance indicator weighting [72]; Cichowicz et al. (2015) developed a dynamic energy consumption model incorporating environmental conditions and operational profile variables to achieve closed-loop energy efficiency management for container ships [73].

Current challenges center on insufficient robustness of intelligent algorithms and the need for higher system integration. He Yapeng et al. (2021) pointed out that domestic and foreign energy efficiency management still mainly relies on offline analysis, with inadequate dynamic online

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optimization [74]; Beşikçi et al. (2016) showed that although neural-network-based decision support systems can optimize speed and trim, larger datasets are needed to enhance generalization ability [75].

7. Conclusion

This review systematically analyzes the technological pathways for improving ship energy efficiency and reducing emissions under the IMO's "dual carbon" goals. The research shows that the collaborative application of hull line optimization, high-efficiency propulsion systems, hybrid power integration, and exhaust aftertreatment technologies such as SCR can effectively reduce ship carbon intensity. Alternative fuels such as ammonia, hydrogen, and methanol, although possessing the potential for low-carbon operation throughout their life cycle, still face challenges related to technological maturity, economic viability, and insufficient infrastructure. In the future, it is necessary to break through key technologies such as high-energy-density energy storage, low-cost green fuels, intelligent energy efficiency control, and carbon capture, and to deepen the development of digital twins and multi-energy collaborative management, so as to promote the shipping industry to achieve its carbon neutrality goal by 2050.

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References

[1] Zhang, Z. W., & Wang, J. N. (1998). Crane design manual. China Railway Press. (In Chinese)

[2] Li, C., Yin, W. Q., & Feng, X. B. (2012). Brushless DC motor stepless speed regulation system based on fuzzy adaptive PI controller. Journal of Mechanical & Electrical Engineering, 29( ), 49–52.

[3] China National Standardization Management Committee. (2008). Specifications of crane design. China Standardization Press.

[4] Liu, J., Chen, E. L., & He, Z. T. (2009). [Article title not available]. Journal of Shi Jia Zhuang Railway Institute (Natural Science), 22(4), 40–42.

[5] Zeng, Q. D., & Li, Q. E. (2012). [Article title not available]. Progress in Civil Engineering, 32(9), 3077–3080.

[6] Weld Laboratory of China. (n.d.). [Homepage]. http://www.weld.labs.gov.cn

[7] Sun, X. X., Qiao, J. P., & Li, R. Z. (2020). Development of auxiliary calculation system for ship main engine energy consumption distribution. Shipbuilding of China, 61(1), 150–156.

[8] Soultatis, C. (2004). Systems modeling for electric ship design [Doctoral dissertation, Massachusetts Institute of Technology].

[9] Burkov, A. F., Mikhanoshin, V. V., & Van, N. K. (2021). Energy losses in electrical networks. In *Proceedings of the International Conference on Industrial Engineering* (pp. 384–393). Cham, Switzerland.

[10] Jiang, Y., Wang, Z., Ma, Y., et al. (2022). Supercritical CO2 power cycle and ejector refrigeration cycle for marine dual fuel engine efficiency enhancement by utilizing exhaust gas and charge air heat. Journal of Marine Science and Engineering, 10(10), 1404.

[11] Ouchi, K. (2010). Technology concept for half fuel oil consumption vessel. Marine Engineering, 45(Special), 998–1003.

[12] Zhang, C., He, Y., & Zhang, D. (2020). Ship propulsion system. In W. Cui, S. Fu, & Z. Hu (Eds.), Encyclopedia of ocean engineering (pp. 28:1–9). Springer.

[13] Zhou, T. T. (2015). Exergy analysis and software development of ship total energy thermal system [Doctoral dissertation, Harbin Engineering University].

ISSN: 2710-0588

[14] Tao, G. H., Gui, Y., & Liu, B. (2023). Analysis of emission and future technology pathways for marine low-speed engines under the dual-carbon strategy. Ship Engineering, 45(10), 19–29.

[15] Karanasiou, A. P. (2021). Cruise shipping and emissions in Mediterranean ports [Doctoral dissertation, University of Piraeus].

[16] He, W. (2024). Research on air pollution modeling and emission inventory methodology: A case study of Shanghai Yangshan Port. E3S Web of Conferences, 536, 03005.

[17] Sun, X., Tian, Z., & Malekian, R. (2018). Estimation of vessel emissions inventory in Qingdao port based on big data analysis. Symmetry, 10(10), 452.

[18] Zhou, C., Tang, W., & Ding, Y. (2024). Analysis of carbon emission reduction paths for ships in the Yangtze River: The perspective of alternative fuels. Journal of Marine Science and Engineering, 12(6), 947.

[19] Lodewyk, K. (2022). High strength structural steel in ship and marine engineering structures.

[20] Miller, J. D., & Façanha, C. (2014). The state of clean transport policy: A 2014 synthesis of vehicle and fuel policy developments.

[21] Bakar, N. N. A., Guerrero, J. M., & Vasquez, J. C. (2021). A review of the conceptualization and operational management of seaport microgrids on the shore and seaside. Energies, 14(23), 7941.

[22] Pyć, D. (2018). ECA compliance and enforcement–legal regime for ships. SHS Web of Conferences, 58, 01026.

[23] Wang, Z., Ma, Q., & Zhang, Z. (2023). A study on monitoring and supervision of ship nitrogen-oxide emissions and fuel-sulfur-content compliance. Atmosphere, 14(1), 175.

[24] Jacoby, M. (2022). The shipping industry looks for green fuels. Chemical & Engineering News, 100.

[25] Månsson, S. (2017). Prospects for renewable marine fuels. Chalmers University of Technology.

[26] Kågeson, P. (2009). Market-based instruments for NOx abatement in the Baltic Sea.

[27] Wang, Y., & Wright, L. A. (2021). A comparative review of alternative fuels for the maritime sector: Economic, technology, and policy challenges for clean energy implementation. World, 2(4), 456–481.

[28] Liao, L. H. (2021). Research on adaptive control strategy of ship electric propulsion system [Doctoral dissertation, Wuhan University of Technology].

[29] Yin, H., Lan, H., & Hong, Y. Y. (2023). A comprehensive review of shipboard power systems with new energy sources. Energies, 16(5), 2307.

[30] SharpiloShutterstock, A., & Our Mission. (2021). ABS advisory on decarbonization applications for power generation and propulsion systems.

[31] Vidović, T., Šimunović, J., & Radica, G. (2023). Systematic overview of newly available technologies in the green maritime sector. Energies, 16(2), 641.

[32] Wang, X., Zhu, J., & Han, M. (2023). Industrial development status and prospects of the marine fuel cell: A review. Journal of Marine Science and Engineering, 11(2), 238.

[33] Zhang, Y. Q. (2024). Application of hydrogen fuel cell in marine power. Science and Technology of Engineering, Chemistry and Environmental Protection, 1(1), 1–5.

[34] Albers, A., Ruoff, S., & Bause, K. (2020). Introduction and investigation of a method for the synthesis and selection of hybrid electric vehicle drivetrain design in the early stage of product generation engineering (PGE). In *Proceedings of the Design Society: DESIGN Conference* (Vol. 1, pp. 787–796).

[35] Kolodziejski, M., & Michalska-Pozoga, I. (2023). Battery energy storage systems in ships' hybrid/electric propulsion systems. Energies, 16(3), 1122.

[36] Zhu, J. (2024). Research on battery hybrid energy storage system. Journal of Shanghai Ship and Shipping Research Institute, 47(3), 43–50.

[37] Dall'Armi, C., Pivetta, D., & Taccani, R. (2023). Hybrid PEM fuel cell power plants fuelled by hydrogen for improving sustainability in shipping: State of the art and review on active projects. Energies, 16(4), 2022.

ISSN: 2710-0588

[38] Karvounis, P., Dantas, J. L. D., & Tsoumpris, C. (2022). Ship power plant decarbonisation using hybrid systems and ammonia fuel—A techno-economic–environmental analysis. Journal of Marine Science and Engineering, 10(11), 1675.

[39] Rizky, I., Kamaruddin, A., & Susanto, S. E. (2022). Transformation of monohull to catamaran hybrid (diesel-PV) fishing vessels to reduce exhaust emissions. International Journal of Marine Engineering Innovation and Research, 7(4), 261–269.

[40] Zhang, C., Lu, T., & Wang, Z. (2023). Research on carbon intensity prediction method for ships based on sensors and meteorological data. Journal of Marine Science and Engineering, 11(12), 2249.

[41] Zhang, Z., Dong, R., & Lan, G. (2023). Diesel particulate filter regeneration mechanism of modern automobile engines and methods of reducing PM emissions: A review. Environmental Science and Pollution Research, 30(14), 39338–39376.

[42] Wang, Z. Y., Zhang, J. F., & Ji, Y. L. (2017). Research progress on emission control of ship exhaust pollutants. Chemical Industry and Engineering Progress, 36(6), 2289–2297.

[43] Lin, X. Y. (2017). High-speed railway and new pattern of economic and social development (2nd ed.). Social Sciences Academic Press.

[44] Aakko-Saksa, P., Lehtoranta, K., & Vesala, H. (2025). Ash generation options for accelerated testing of marine diesel particulate filters (Technical Paper 138). 31st CIMAC World Congress.

[45] Jiang, X. D., Mo, Z. Y., & Wang, Y. S. (2022). Application of active regeneration electrostatic adsorption technology in marine engine exhaust PM treatment. China Storage & Transport, 2022(6), 84–85.

[46] Schaml, S., Rothe, D., & Lutz, F. (2017). Highly integrated exhaust gas aftertreatment systems in heavy-duty applications. In *Internationaler Motorenkongress 2017* (pp. 543–554). Springer Fachmedien.

[47] Savva, P. G., Fessas, Y., & Efstathiou, A. M. (2023). Development of a novel De-NOx technology for the aftertreatment of ship exhaust gases. Applied Sciences, 13(20), 11356.

[48] Ellian, O., Hegazy, E. S., & Tawfik, A. A. (2016). Ship emissions reduction using alternative fuels and abatement technology.

[49] Li, K. (2021). Control technology and supervision of sulfur oxide emission from ships.

[50] Wurster, R., Weindorf, W., & Zittel, W. (2014). LNG as an alternative fuel for the operation of ships and heavy-duty vehicles.

[51] Sastre Buades, L. (2017). Implementation of LNG as marine fuel in current vessels: Perspectives and improvements on their environmental efficiency [Doctoral dissertation, Universitat Politècnica de Catalunya].

[52] Van Hoecke, L., Laffineur, L., & Campe, R. (2021). Challenges in the use of hydrogen for maritime applications. Energy & Environmental Science, 14(2), 815–843.

[53] Fachada, N., & David, D. (2024). Artificial intelligence in modeling and simulation. Artificial Intelligence in Modeling and Simulation, 17, 1.

[54] Wang, J. Z., Jiang, Z. H., & Xie, W. K. (2024). Research progress on exhaust gas treatment technology for marine ammonia fuel combustion. Ship Science and Technology, 46(1), 8–14.

[55] Memmler, M., Lauf, T., & Wolf, K. (2016). Emissionsbilanz erneuerbarer Energieträger, Bestimmung der vermiedenen Emissionen im Jahr.

[56] Infinita Biotech Private Limited. (2020). BIOVOICE KNOW, SHARE & GROW ANNUAL 2020.

[57] Kamat, S., Botting, D., & Bingham, C. M. (2025). A new philosophy for the development of regional energy planning schemes. Sustainability, 17(8), 3295.

[58] Imhoff, T. B., Gkantonas, S., & Mastorakos, E. (2021). Analysing the performance of ammonia powertrains in the marine environment. Energies, 14(21), 7447.

[59] Chavando, A., Silva, V., & Cardoso, J. (2024). Advancements and challenges of ammonia as a sustainable fuel for the maritime industry. Energies, 17(13), 3183.

[60] Lee, H., & Lee, M. J. (2021). Recent advances in ammonia combustion technology in thermal power generation system for carbon emission reduction. Energies, 14(18), 5604.

[61] Xu, X., Liu, E., & Zhu, N. (2022). Review of the current status of ammonia-blended hydrogen fuel engine development. Energies, 15(3), 1023.

[62] Zis, T. P. V., Psaraftis, H. N., & Ding, L. (2020). Ship weather routing: A taxonomy and survey. Ocean Engineering, 213, 107697.

[63] Yang, L., Chen, G., & Zhao, J. (2020). Ship speed optimization considering ocean currents to enhance environmental sustainability in maritime shipping. Sustainability, 12(9), 3649.

[64] Li, F. (2020). Research on ship energy consumption monitoring system based on computer intelligent technology. Journal of Physics: Conference Series, 1648(2), 022054.

[65] Wang, K., Wang, Z. Y., & Huang, L. Z. (2023). Review of ship energy efficiency intelligent optimization based on big data and artificial intelligence. Navigation of China, 46(1), 155–162.

[66] Yuan, Y., Wang, X., & Tong, L. (2023). Enhancement method of series hybrid ship energy efficiency for speed and energy collaborative optimization. IET Electrical Systems in Transportation, 13(2), e12085.

[67] Cai, X. C., Li, X., & Huang, J. T. (2024). Optimization of ship energy efficiency ratio based on SCE-UA algorithm. Ship Engineering, 46(9), 56–63.

[68] Shao, T., Du, W., & Ye, Y. (2024). A novel virtual arrival optimization method for traffic organization scenarios. Sustainability, 16(1), 403.

[69] Choi, G. H., Lee, W., & Kim, T. (2023). Voyage optimization using dynamic programming with initial quadtree based route. Journal of Computational Design and Engineering, 10(3), 1185–1203.

[70] Wang, L., Chen, J., & Zhang, Y. (2024). Research on data mapping and fusion method of ship production workshop based on digital twins. Measurement and Control, 57(9), 1255–1267.

[71] Bacalja Bašić, B., Krčum, M., & Jurić, Z. (2024). Propeller optimization in marine power systems: Exploring its contribution and correlation with renewable energy solutions. Journal of Marine Science and Engineering, 12(5), 843.

[72] Gualeni, P., & Maggioncalda, M. (2018). Life cycle ship performance assessment (LCPA): A blended formulation between costs and environmental aspects for early design stage. International Shipbuilding Progress, 65(2), 127–147.

[73] Cichowicz, J., Theotokatos, G., & Vassalos, D. (2015). Dynamic energy modelling for ship life-cycle performance assessment. Ocean Engineering, 110, 49–61.

[74] He, Y. P., Yan, X. P., & Fan, A. L. (2021). Development status and prospects of ship intelligent energy efficiency management technology. Journal of Harbin Engineering University, 42(3), 317–324.

[75] Beşikçi, E. B., Arslan, O., & Turan, O. (2016). An artificial neural network based decision support system for energy efficient ship operations. Computers & Operations Research, 66, 393–401.