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A Review of Ship Energy Loss, Emission Characteristics and IMO Compliance Energy-Saving Technologies

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Abstract

Global maritime decarbonization driven by IMO regulations has become the core constraint for modern shipping operations. This study adopts bibliometric analysis (2015–2025) and PRISMA-based systematic review (2018–2025) to comprehensively investigate ship energy loss mechanisms, emission distribution characteristics and mainstream energy efficiency improvement technologies. This paper fully analyzes power system partial-load loss, thermal heat dissipation and actual energy waste data of merchant ships. The mandatory regulatory system including EEDI, EEXI, CII and SEEMP is systematically interpreted. Typical energy-saving technologies covering hull optimization, power system retrofitting, waste heat recovery and operational management are summarized. A quantitative comparison of technical performance, cost and emission reduction potential is presented. On this basis, staged low-carbon paths for different ship types are proposed. The research results can provide practical references for shipping enterprises to achieve CII compliance and ship energy-saving transformation.

Keywords

Maritime decarbonization; ship energy loss; ship emission; IMO regulations; CII compliance; energy-saving technology.

1. Introduction

Maritime shipping undertakes over 80% of global trade cargo and produces massive greenhouse gas emissions [1]. To control maritime pollution and promote low-carbon shipping, the International Maritime Organization (IMO) has implemented a complete regulatory system including EEDI, EEXI, CII and SEEMP, forming full-life-cycle carbon supervision for new and existing vessels. Ship energy loss and uncontrolled emissions seriously restrict corporate compliance and sustainable operation.

Current studies mostly focus on single energy-saving technology, lacking systematic integration of energy dissipation mechanism, emission characteristics and policy adaptation [2]. To fill this gap, this paper adopts bibliometric analysis and systematic review framework. It integrates all typical ship energy efficiency technologies, compares their applicability, and proposes phased decarbonization strategies. This study aims to provide comprehensive technical support for ship low-carbon transformation and IMO regulatory compliance.

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2. Methodology

2.1. Bibliometric Analysis Setup

Bibliometric analysis is conducted based on the Web of Science and Scopus databases, covering a time window of 2015-2025. This extended period facilitates the identification of keyword evolution, research clustering and shifting hotspots within the field of ship energy efficiency. In contrast, the systematic review adopted in this work employs a narrower timeframe (2018–2025) to guarantee the timeliness and reliability of technical data and policy-related research outcomes.

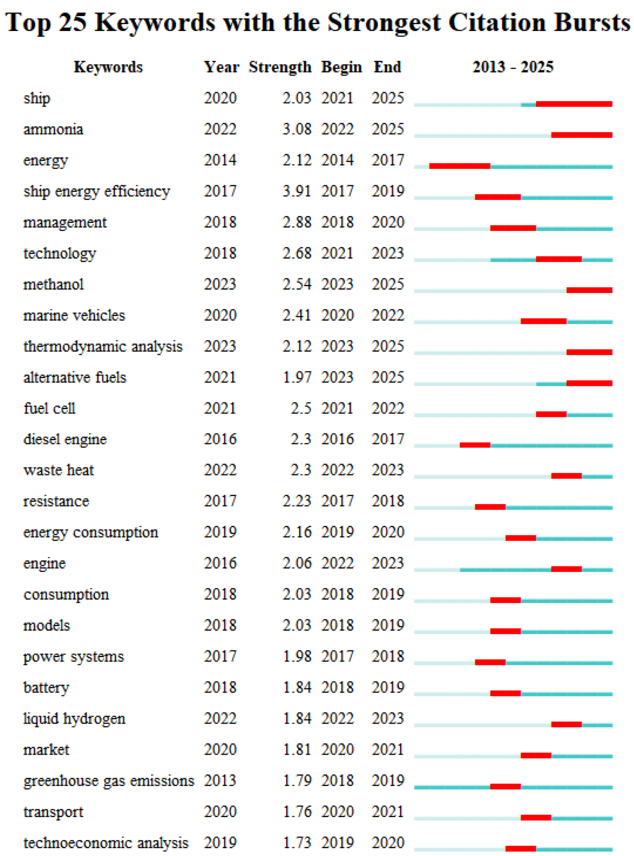

Figure 1. Top 25 Keywords with the Strongest Citation Bursts

The keyword burst detection results as shown in Fig 1, reveal the evolutionary trend of research focus. Early studies mainly concentrated on diesel engine fuel consumption and marine power system optimization. Since 2020, topics including CII compliance, low-carbon management and alternative marine fuels have attracted growing attention. This transition demonstrates that maritime research is gradually shifting from pure technical exploration toward regulation-oriented practical research under global decarbonization demands.

2.2. Systematic Review Screening (PRISMA)

The keyword burst detection results as shown in Fig 1, reveal the evolutionary trend of research focus. Early studies mainly concentrated on diesel engine fuel consumption and marine power system optimization. Since 2020, topics including CII compliance, low-carbon management and alternative marine fuels have attracted growing attention. This transition demonstrates that maritime research is gradually shifting from pure technical exploration toward regulation-oriented practical research under global decarbonization demands.

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2.3. Synthesis of Existing Technology Assessments

Existing studies have verified the emission reduction potential of various ship energy-saving measures, but most reviews lack staged path planning matching IMO phased targets and differentiated analysis for different ship operation scenarios. This paper innovatively integrates energy loss mechanism, emission characteristics and regulatory requirements, and forms a multi-technology collaborative optimization scheme suitable for short-term and medium-long-term ship decarbonization.

3. RIMO Mandatory Energy Efficiency Regulatory Framework

3.1. EEDI

$$EEDI = \frac{CO_2 \text{ Emission}}{\text{Transport work}} = \frac{\text{Power} * \text{Specific fuel consumption} * CO_2 \text{ conversion factor}}{\text{Capacity} * \text{Speed}} \tag{1}$$

The Energy Efficiency Design Index (EEDI) was formally introduced through amendments to MARPOL Annex VI, marking the first global mandatory regulation to control CO_2 emissions from new ships [3] It serves as a design-stage metric to quantify a vessel's inherent carbon intensity, allowing shipowners and operators to evaluate the emission reduction potential of different design and technological improvements [3]. The index essentially measures the CO_2 emissions generated per unit of transport work under specific cargo capacity and sailing speed conditions. Its basic expression is as follows:

This simplified formula clearly reflects the core principle of EEDI: emissions are directly proportional to engine power and fuel consumption, while inversely proportional to the ship's cargo capacity and operating speed. By setting mandatory EEDI benchmarks, the IMO drives improvements in ship design, propulsion efficiency, and low-carbon fuel adoption to reduce the carbon intensity of new vessels.

3.2. EEXI

The Energy Efficiency Existing Ship Index (EEXI) was formally introduced by the International Maritime Organization (IMO) through amendments to MARPOL Annex VI in November 2020, and entered into force in 2023, applying to all vessels above 400 GT subject to MARPOL Annex VI regulations [4]. As a technical complement to the Energy Efficiency Design Index (EEDI) for newbuild ships, EEXI establishes standardized CO_2 emission benchmarks based on a vessel's installed engine power, transport capacity, and design speed, defining the allowable emissions per unit of transportation work [5]. Notably, unlike operational indicators such as CII, EEXI is a static, design-based metric that does not require continuous onboard monitoring, focusing instead on the inherent technical efficiency of the vessel's configuration.

To translate these long-term strategic goals into concrete operational practices, the IMO has established and implemented a mandatory Carbon Intensity Indicator (CII) management system. This system came into effect in 2023 for international voyage ships of 5,000 gross tonnage and above, requiring them to calculate and obtain an annual rating of their CII performance (A-E). According to the regulations, ships rated E, or D for three consecutive years must develop and implement an approved Ship Energy Efficiency Management Plan (SEEMP). This mandatory compliance requirement directly and powerfully drives the adoption of measures such as fleet optimsation and technological innovations in energy efficiency, serving as a key policy lever that connects the IMO's 2050 strategic goals to daily ship operations and management.

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3.3. CII

To translate these long-term strategic goals into concrete operational practices, the IMO has established and implemented a mandatory Carbon Intensity Indicator (CII) management system. This system came into effect in 2023, applying to most international voyage ships of 5,000 gross tonnage and above [6], requiring them to calculate and obtain an annual rating of their CII performance, graded from A to E. Ships are evaluated based on their operational carbon intensity, with ratings reflecting their relative performance against regulatory benchmarks . This mandatory compliance requirement directly drives the adoption of measures such as fleet optimisation and technological innovations in energy efficiency, serving as a key policy lever that connects the IMO's 2050 strategic goals to daily ship operations and management.

3.4. SEEMP

A core complementary measure to the CII rating system is the Ship Energy Efficiency Management Plan (SEEMP) [7]. According to the regulations, ships rated E, or D for three consecutive years, must develop and implement an approved SEEMP. The plan serves as a structured roadmap for identifying, implementing, and monitoring energy efficiency improvement measures on board, covering operational adjustments, maintenance practices, and technology upgrades. By formalising corrective actions for underperforming vessels, SEEMP ensures that the CII framework translates into tangible, continuous improvements in a ship's energy efficiency over its operational lifecycle.

4. Energy Loss Mechanism of Ship Power Systems

4.1. Power System and Auxiliary Machinery

Auxiliary Machinery System (mainly diesel generators) accounts for about 8% of energy consumption. For example, a 4-stroke medium-speed diesel generator typically has a rated power of 1,300 kW/unit and a fuel consumption rate of 184 g/kWh. Its electrical energy conversion process involves multiple losses. When Soulfatis analysed the power system, it was found that generator loss is about 3%, main switchboard loss is 0.2%, frequency converter loss is 1.5%, and electric propulsion motor loss is 3-4%. The cumulative losses reduce the overall efficiency to 90-92%. These losses originate from harmonics, I^2R copper losses, and iron-core eddy-current losses, particularly when operating redundantly under partial load, thereby exacerbating energy consumption.

4.2. Thermal Systems and Waste Heat Recovery

The boiler system accounts for approximately 3% of total energy consumption and has an evaporation capacity of approximately 50,000 kg/h. Significant losses occur during heat transfer. Jiang's energy balance diagram indicates that only 49.3% of fuel energy is converted into shaft power, while exhaust gas heat loss accounts for 25.5%, cooling water loss for 5.2%, and radiation loss for 0.6%. Waste heat boilers can improve efficiency by 4.83% through recovering exhaust-gas heat, although the thermodynamic cycle entails energy destruction. Based on the Seiliger cycle model, Li Jifeng validated that freshwater production using jacket water can recover 5.06% of waste heat. However, operational fluctuations (e.g., under low-load conditions) reduce the heat-recovery rate, indicating dynamic instability of the system[8].

5. Mainstream Energy-Saving and Decarbonization Technologies for Ships

5.1. Hull Structure Design and Optimization Technologies

The Ship Energy Efficiency Design Index (EEDI) is a mandatory international regulation established by the International Maritime Organisation (IMO) to evaluate the energy efficiency

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level of new ships. By setting progressively stricter minimum efficiency thresholds, the EEDI aims to drive the adoption of innovative technologies and optimised design methods, thereby reducing the carbon dioxide emissions of the global fleet. To achieve the phased EEDI compliance targets, ship design and optimisation technologies have become a critical pathway. The core aspects include hull hydrodynamic optimisation, lightweight structural design, multi-objective collaborative optimisation, and simulation-based design methods, which collectively minimise ship resistance and energy consumption from the design source.

5.1.1. Structural Light Weighting and Material Innovation

Structural optimisation focuses on lightweight design, which helps improve deadweight capacity in the EEDI denominator and reduce hull resistance. Zhang et al. [9] reviewed the application of composite materials in ships, indicating that carbon fiber-reinforced resin-based sandwich structures can reduce weight by over 30% while enhancing structural stiffness. Additionally, Li et al. achieved a 45% weight reduction in the superstructure through a steel-composite hybrid connection design; finite element analysis showed that the stress concentration of the optimised structure was only 12%-38% of that of the original component.

5.1.2. Optimization Algorithms and MDO

In the field of optimisation algorithms, Zhang Baoji et al. categorised methods into three classes: traditional gradient-based algorithms, heuristic global algorithms, and hybrid optimisation algorithms. Among these, multi-objective algorithms such as Genetic Algorithms (GA) and NSGA-II are widely used due to their effectiveness in handling nonlinear constraints [10]. Zhao Liuping et al. emphasised that heuristic algorithms are more adaptable to the structural complexity of ships than classical methods. The introduction of surrogate model technology has made ship-level optimisation feasible, particularly as dynamic surrogate models can enhance local accuracy by sequentially updating sample points. Zhu Shuwei et al. further proposed a data-driven evolutionary optimisation theory, which reduces the number of high-fidelity evaluations by dynamically updating surrogate models. Its mathematical model centres on minimising the resistance objective function f(x) by searching for the solution vector X within the design space D subject to geometric constraints, such as wetted surface area and displacement volume.

Multidisciplinary Design Optimisation is a critical pathway for improving comprehensive energy efficiency. Papanikolaou, within the HOLISHIP project, proposed a parametric "digital sibling" model that explores the collaborative design space of hull geometry, cabin layout, and propulsion systems using Sobol sequence sampling [11]. Feng Baiwei established a multidisciplinary optimisation platform for ship hull lines, implementing parametric master modelling via NURBS surface modification techniques and generating specialised view models for resistance and sea-keeping disciplines, thereby validating the engineering value of a variable-complexity evolutionary design mode [12]. Practical case studies demonstrate the significant benefits of design optimisation for improving energy efficiency. Du Wei implemented a route-speed collaborative optimisation for a 300,000 DWT VLCC, integrating real-time meteorological data for dynamic loading, resulting in a 16.66% reduction in fuel consumption per nautical mile and a 22.8% reduction in CO_2 emissions. Raphael Zaccone utilised a genetic algorithm to optimise power allocation in a diesel-electric propulsion system, achieving a 15-20% improvement in fuel efficiency [13].

Ship hull resistance is mainly divided into two components: gravitational (wave-making) resistance and viscous resistance. Viscous resistance, derived from boundary layer separation-induced pressure drag and frictional drag associated with the surface condition of the hull and appendages, accounts for the majority of total resistance in low-Froude-number vessels, and remains the dominant resistive component even at high sailing speeds where wave-making resistance becomes non-negligible.

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According to the American Bureau of Shipping (ABS) [14], hull surface roughness caused by marine runoff and fouling has a significant impact on frictional resistance. For different vessel types, a 10-20 μm increase in hull roughness can raise total resistance by 0.5% to 1%, with more pronounced effects on low-speed ships. Historical data shows that average hull roughness ranges from 10 to 25 μm depending on the coating system, highlighting the critical role of hull cleaning in maintaining fuel efficiency.

Multiple factors, including seawater temperature, salinity, organism density in operating areas, navigation speed, anchoring duration, and the type of antifouling protection applied, govern the accumulation rate of hull incrustation. Without scheduled maintenance over a 10-year operational period, hull fouling can increase advance resistance by 15% to 50% (average 30%). Dry-docking maintenance, including complete fouling removal and hull painting with or without antifouling protection, effectively mitigates the additional resistance caused by barnacle accumulation. The optimal timing of hull maintenance should be determined by integrating performance monitoring results (to quantify extra resistance), cost analysis of alternative maintenance strategies, and the opportunity cost of vessel off-hire during commissioning.

Propeller surface roughness stems from either biological fouling or physical damage (impact, cavitation erosion, and corrosion). Merchant vessel propellers are typically fabricated with 70% copper-containing alloys to reduce biological fouling; however, copper cannot inhibit all types of scale formation, so regular fouling removal is required. Although the absolute efficiency loss from propeller fouling is smaller than that from hull fouling, it can still lead to a 6% increase in total resistance and cannot be disregarded. Globally, hull fouling accounts for approximately 9% of annual fuel consumption in the shipping fleet, corresponding to an extra fuel expenditure of USD 16 billion and roughly 80 million tons of excess CO_2 emissions [15]. Since propeller maintenance requires far fewer resources than hull maintenance, propeller cleaning and polishing are cost-effective measures to improve vessel energy efficiency.

A study in [16] proposed a method to assess a ship's actual propulsive efficiency using continuous on-board measurements combined with corresponding meteorological and oceanographic (metocean) data. This technique enables accurate evaluation of real-time vessel operating conditions and supports condition-based maintenance, especially for hull and propeller fouling control, which aligns with the core objectives of reducing fuel consumption, maintaining service speed, and ensuring compliance with emission standards. Notably, propeller fouling has a greater impact on ship performance than hull fouling on a per-unit-area basis [17]. A recent comprehensive review in [18]. systematically summarized bio-fouling organisms and their adhesion mechanisms, potential risks of antifouling paints, and high-efficiency hull cleaning technologies; meanwhile, the application of ultrasonic technology for ship fouling prevention is gaining increasing attention [15].

5.2. A Comparative Analysis and Strategic Pathways for CII Compliance

To systematically evaluate energy-efficiency technologies within the CII framework, Table 1 presents a consolidated comparison of the key pathways discussed in this chapter. Structured around the dual-perspective of energy demand-side management and supply-side decarbonization, it synthesises critical parameters, energy-saving potential, technological maturity, cost implications, and primary application scenarios, serving as a decision-support tool for stakeholders to identify viable technology portfolios tailored to specific ship types, operational profiles, and CII targets.

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Table 1. Comparative Summary of Core Ship Energy Efficiency Improvement Technologies

Technology Category	Specific Technologies	Energy-Saving Potential	Technology Maturity	CAPEX(USD per vessel)	Annual OPEX Saving(USD/year)	Estimated Payback Period(Years)	Primary Applicable Ship Types/Scenarios
Hull Design Optimization	Linear optimization/Lightweight materials	5-15%	High	500000-2000000	100000-300000	3-7	Newbuilding
Propulsion System Efficiency	High-efficiency propeller, PBCF	3-8%	High	200000-800000	50000-150000	2-5	Newbuilding/Refitted ship
Hybrid Power Systems	Diesel-electric hybrid	10-25%	Medium-High	1000000-3000000	200000-500000	4-8	Ferries, Harbour tugs, Cruise ship
Wind-Assisted Propulsion	Rotor sail, Wing Sail	5-20%	Medium	800000-2500000	150000-400000	3-6	Bulk carriers, Tanker(Route matching)
Solar Photovoltaic	Deck photovoltaic system	1-5%	High	100000-500000	20000-80000	5-10	Auxiliary power supply, Limited by deck area

* Information from [19-21]

The analysis in Table 1 reveals a hierarchical and complementary relationship among the technologies. Foundational measures (e.g., hull form optimisation, propulsion retrofitting) target intrinsic energy demand, delivering stable efficiency gains of 5-15% by reducing hydrodynamic resistance and mechanical losses. In contrast, system-level and energy-source technologies (e.g., hybrid power, wind-assisted propulsion) act as performance multipliers, achieving additional savings of 10-25% through dynamic energy management or renewable integration, which is ideal for vessels with variable operating profiles (e.g., ferries, short-sea shipping).

From a CII compliance perspective, this hierarchy informs a phased strategy: in the short term (1-3 years), combining foundational optimisations with operational measures and hybrid power offers the most cost-effective pathway to immediate reductions in carbon intensity. For medium-to long-term compliance (beyond 5 years), transitioning to low-or zero-carbon carriers (e.g., green methanol, ammonia, hydrogen) becomes imperative, contingent on the development of bunkering infrastructure, reductions in fuel costs, and marine engine adaptations.

It is difficult, if not impossible, to argue that a single measure can be deemed the optimal decarbonization solution for the maritime industry. In fact, in the vast majority of practical operational scenarios, a synergistic combination of multiple technical measures is far more likely to deliver a reliable, realistic and cost-effective decarbonization pathway that aligns with the IMO's phased emission reduction targets and Carbon Intensity Indicator (CII) rating requirements.

The inappropriateness of over-reliance on a single decarbonization measure stems from two core realities of the shipping industry. On the one hand, each individual technology is inherently constrained by its technical characteristics, emission-reduction potential, and application scenarios. For instance, mature energy-saving technologies such as air lubrication systems and high-efficiency propellers can achieve only a 5-15% reduction in carbon intensity [22], which is insufficient to meet the IMO's stringent medium-and long-term decarbonization goals. Emerging zero-carbon fuels such as ammonia and hydrogen, despite their ultimate emission-reduction potential, are currently limited by immature infrastructure, high costs, and technical bottlenecks, rendering large-scale standalone applications unfeasible in the short term. On the other hand, the shipping industry features diverse ship types, operational profiles and navigation routes a one-size-fits-all single technology cannot simultaneously adapt to the heterogeneous decarbonization needs of deep-sea container ships, coastal bulk carriers and inland ferries.

By contrast, integrating multiple decarbonization measures generates a complementary, multiplicative effect that exceeds the emission-reduction potential of individual technologies. A typical synergistic combination may include foundational energy efficiency measures (e.g.,

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hull form optimization and waste heat recovery) to reduce the baseline energy consumption of ships, coupled with system-level decarbonization technologies (e.g., wind-assisted propulsion and hybrid power systems) to further cut fuel consumption and emissions, and supplemented by operational optimization strategies (e.g., intelligent route planning and trim adjustment) to maximize the overall energy efficiency throughout the entire voyage. This multi-layered combination not only mitigates the technical and economic risks of relying on a single technology but also enables flexible adjustment of the technology portfolio based on the CII rating of individual ships, the maturity of supporting infrastructure, and shipowners' operational budgets, thereby ensuring the feasibility and sustainability of decarbonization practices.

This synergy principle is also validated by real-world industrial applications. For example, the integration of Norsepower's rotor sail system with Syroco's AI-driven weather routing technology on Socatra's Alcyone oil tanker achieved a 21% reduction in fuel consumption [23], an effect that far exceeds the simple sum of the emission reduction potential of each individual technology. This practical case fully demonstrates that the combination of multiple measures is not merely a passive choice to compensate for the limitations of single technologies, but an active and scientific strategy to unlock the full decarbonization potential of the shipping industry.

Critically, no single technology constitutes a universal panacea for maritime decarbonization. The most substantial gains stem from technical synergy-for instance, the integration of wind-assisted propulsion with weather routing, or alternative fuels paired with optimised combustion and exhaust after-treatment. A salient case is the "Alcyone" oil tanker owned by Socatra, where Norsepower's rotor sail system was synergistically integrated with Syroco's AI-driven weather-routing technology. This integration achieved fuel savings of up to 21% [24] and, more importantly, the synergistic effect yielded an overall energy efficiency improvement that far exceeded the simple summation of individual technologies. Preliminary data indicate a doubling of voyage performance. This case strongly validates that real-time route optimisation via intelligent algorithms, when coordinated with wind-assisted propulsion systems, maximises energy efficiency to a degree that outperforms the isolated application of either technology.

5.3. Rationale for the Proposed Phased Decarbonization Timeline

The phased decarbonization timeline and corresponding technical measures proposed in this review are not subjective recommendations, but rather rigorously justified by three interrelated, evidence-based core pillars: strict alignment with the latest IMO regulatory requirements and statutory targets, precise matching with the evolutionary trajectory of maritime decarbonization Technology Readiness Levels (TRL), and full compliance with the techno-economic feasibility and industrial application principles of the global shipping industry. This multi-dimensional justificatory framework ensures that the proposed timeline is not only consistent with the strategic goals of global carbon neutrality but also practically feasible for industrial implementation.

5.3.1. Alignment with IMO Mandatory Regulatory Targets

The formulation of this timeline is fundamentally anchored in the IMO's Revised Initial Strategy on Reduction of GHG Emissions from Ships (2023) and the mandatory Carbon Intensity Indicator (CII)/Energy Efficiency Existing Ship Index (EEXI) management system, which has been fully implemented since 2023 [25]. These authoritative global regulatory rules set non-negotiable time-bound targets and mandatory emission-reduction requirements for maritime decarbonization. Short-term measures (2025-2027) are closely aligned with the phased CII rating improvement requirements, which mandate that all international ships of 5,000 gross tonnage and above meet the minimum EEXI compliance standards and avoid consecutive D/E-

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grade CII ratings. This renders the large-scale retrofitting and application of mature energy-saving technologies (e.g., air lubrication systems, high-efficiency propellers) an urgent industrial need for the global shipping fleet. The mid-term milestone (2030) directly aligns with the IMO's statutory emission reduction target, at least a 40% reduction in shipping carbon intensity compared to 2008 [26] levels, requiring the widespread adoption of low-carbon drop-in fuels (e.g., green methanol) and system-level decarbonization technologies (e.g., wind-assisted propulsion, hybrid power systems) in deep-sea shipping by that time. The long-term goal (2040-2050) responds to the IMO's ultimate vision of achieving net-zero greenhouse gas emissions from international shipping, an inevitable direction of industrial transformation driven by global climate governance and a fundamental prerequisite for the shipping industry to contribute to the temperature control goals of the Paris Agreement.

5.3.2. Matching with Maritime Decarbonization TRL Trajectories

The deployment timelines of various decarbonization technologies in the proposed schedule are strictly aligned with the TRL evolution of maritime low-carbon technologies, based on the latest technical assessment reports from the International Council on Clean Transportation (ICCT) and leading maritime engineering research institutions (e.g., Shanghai Jiao Tong University, Norwegian Marine Technology Research Institute) [27]. In the short term (2025-2027), the focus is on mature technologies with TRL 8-9 (e.g., hull form optimisation, waste heat recovery, SCR exhaust after-treatment). These technologies have been validated through large-scale industrial applications, require no additional R&D investment, and can be directly retrofitted onto existing ships to achieve immediate, stable emission reductions (basic measures can reduce carbon intensity by 5-15%) [28]. In the mid-term (2028-2035), the core priority is to promote emerging low-carbon technologies with TRL 6-7 (e.g., methanol/ammonia dual-fuel engines, rotor-sail wind-assisted propulsion, shore power connection systems). This 7-year time window is designed to address remaining industrialisation barriers (e.g., the construction of global green fuel bunkering infrastructure and optimising ammonia fuel combustion stability) and to complete commercial scaling, with an expected additional 10-25% reduction in carbon intensity. In the long term (2036-2050), the focus shifts to transformative zero-carbon technologies with TRL 3-5 (e.g., onboard carbon capture and storage (OCCS), hydrogen fuel cells, full electric propulsion for large ships). The 14-year technology development cycle is deemed necessary to achieve R&D breakthroughs, reduce production costs, and establish globally unified safety and application standards. This phase is critical for the shipping industry to meet the IMO's net-zero emission target.

5.3.3. Validation with Techno-Economic Feasibility Principles

The rationality of this timeline is further validated by the techno-economic feasibility curve for maritime decarbonization technologies, supported by data from the latest industry forecasts by authoritative maritime classification societies and research institutions (DNV 2024 Maritime Fuel Forecast, Lloyd's Register 2024 Shipping Decarbonization Techno-Economic Analysis) [29]. First, key application nodes for zero-carbon fuels are determined by projected cost-parity points between low-and zero-carbon fuels and traditional marine gas oil (MGO): green methanol is expected to reach cost parity with MGO by 2030, and green ammonia by 2035. The timeline is precisely aligned with these nodes to ensure shipowners can secure a reasonable return on investment (ROI) for technology retrofitting. Second, the phased technology promotion model aligns with the shipping industry's capital investment capacity, a capital-intensive sector with long payback periods. Avoiding the simultaneous rollout of numerous high-cost emerging technologies effectively reduces burden on shipowners and shipping companies, enhancing the willingness of industrial stakeholders to participate in decarbonization. Third, the timeline fully accounts for the construction cycle of supporting green shipping infrastructure (e.g., green-fuel bunkering ports, shore power facilities), a key

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prerequisite for the large-scale application of low-carbon/zero-carbon technologies. The 5-10 year buffer period between technology R&D and industrial scaling is sufficient to support the global maritime industry in completing the comprehensive construction of a decarbonization infrastructure system. In summary, the phased decarbonization timeline proposed in this review is a scientific and feasible roadmap developed based on global regulatory requirements, technological development laws, and industrial economic realities. It provides a clear and operational implementation direction for the global shipping industry to achieve the IMO's carbon peak and carbon neutrality goals, while laying a solid theoretical and practical foundation for shipowners, shipyards, and maritime policymakers in selecting decarbonization technologies and making decisions.

6. Conclusion

Under the continuous promotion of IMO decarbonization policies, ship energy efficiency improvement has become an inevitable requirement for the sustainable development of global shipping. This paper adopts bibliometric analysis and PRISMA systematic review methods to sort out the research progress of ship energy efficiency and emission reduction from 2015 to 2025. The paper systematically expounds the energy loss mechanism of ship power and thermal systems, analyzes ship emission distribution characteristics and environmental hazards, and comprehensively interprets the four core regulatory systems of EEDI, EEXI, CII and SEEMP.

This study classifies mainstream ship energy-saving technologies and quantitatively compares their emission reduction potential, cost and applicability. The results show that multi-technology collaborative optimization is the only way to realize phased ship decarbonization. Short-term compliance relies on operational management optimization, while long-term low-carbon development depends on equipment upgrading and systematic technical transformation. This review can provide effective technical references and path guidance for shipping enterprises to carry out energy-saving renovation and meet international maritime carbon emission regulations.

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