



Chemical and Environmental Science Archives
(ISSN: 2583-1151)
An International Research Journal

DOI: <https://doi.org/10.47587/CESA.2026.6201>[Review Article](#)

Energy Efficiency Measures in Ship Design and Operation

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Received: Mar 1, 2026/ Revised: Apr 5, 2026/ Accepted: Apr 12, 2026

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Abstract

The maritime transport sector remains a cornerstone of global trade while contributing substantially to anthropogenic greenhouse gas (GHG) emissions and fuel consumption. As regulatory ambition intensifies under the framework of the International Maritime Organization, energy efficiency has emerged as the most immediate, scalable, and cost-effective pathway toward near-term decarbonization. This review presents a structured and systems-oriented synthesis of energy efficiency measures spanning ship design, propulsion technologies, onboard energy management, operational strategies, and digital performance optimization. Design-phase interventions are examined through advances in hull-form optimization, hydrodynamic drag reduction, structural lightweighting, propeller–hull interaction enhancement, and high-efficiency propulsion architectures. The review further evaluates hybridization pathways, alternative fuel readiness, wind-assisted propulsion, and battery integration as transitional solutions that complement efficiency gains. At the operational level, measures including speed optimization, weather routing, trim and ballast management, predictive maintenance, and just-in-time port arrival are assessed for their measurable impact on fuel intensity and carbon performance. The enabling role of digitalization encompassing real-time monitoring, data analytics, and digital twins is critically analyzed as a mechanism for continuous improvement and regulatory compliance under instruments such as EEDI, EEXI, and CII. By integrating technical, operational, and data-driven dimensions, this review highlights synergistic strategies capable of delivering substantial lifecycle energy savings. It argues that sustained maritime decarbonization requires a holistic systems approach in which design excellence, operational discipline, and digital intelligence function as mutually reinforcing components of energy performance optimization.

Keywords: Energy, Efficiency, Ship, Design, and Operation

Introduction

Maritime shipping is a backbone of global trade, handling over 80% of world cargo while consuming large amounts of fuel and contributing substantially to greenhouse gas (GHG) emissions (Early, 2025). Despite improvements in engine efficiency and operational practices, emissions from shipping remain high, and the sector faces growing scrutiny under global decarbonization efforts (Mehta, 2024). Energy efficiency has emerged as the most immediate and cost-effective pathway to reduce fuel consumption and emissions, offering both environmental and economic benefits by lowering operational costs and improving vessel performance (DNV, 2025). These twin pressures from environmental imperatives and economic considerations have driven research, policy development, and technological innovation in the maritime sector.

Regulatory frameworks established by the International Maritime Organization (IMO) provide a key mechanism for improving ship energy performance. Mandatory measures such as the Energy Efficiency Design Index (EEDI) set minimum design-phase efficiency standards for new vessels, while the Energy Efficiency Existing Ship Index (EEXI) applies technical and operational requirements to existing ships to achieve similar efficiency gains (Amararitei, 2025). The Carbon Intensity Indicator (CII) complements these indices by assessing annual operational performance, incentivizing operators to optimize voyage planning, speed, and fuel use (International Maritime Organization, 2026). Together, EEDI, EEXI, and CII represent a shift toward performance-based regulation that integrates both design and operational dimensions, creating measurable pathways to decarbonization.

Technological innovation is central to improving ship energy efficiency. Advanced hull design, hydrodynamic optimization, and computational fluid dynamics (CFD) modeling reduce water resistance and fuel demand (Talip *et al.*, 2025). Onboard propulsion systems have become increasingly efficient, with hybrid configurations, waste heat recovery, and low-carbon fuel readiness offering additional opportunities to minimize energy consumption (DNV, 2025). Moreover, data-driven approaches, including time-series analysis and machine learning, enable operators to monitor and optimize vessel performance for fixed-route shipping and other operational contexts (Abuella *et al.*, 2024). These innovations illustrate how design and technological solutions complement one another to achieve measurable energy performance gains.

Operational measures continue to play a critical role in translating design potential into real-world efficiency. Slow steaming, trim and ballast optimization, and hull and propeller maintenance have been demonstrated to reduce fuel consumption significantly (Elkafas and Shouman, 2021; Yang and Byun, 2024). Additionally, environmental information, such as tidal currents and weather patterns, can be leveraged to improve routing efficiency and minimize energy usage (Yang

and Byun, 2024). The integration of operational best practices with digital monitoring and predictive analytics further enables continuous performance optimization, allowing ship operators to meet regulatory requirements while maximizing economic benefits (Talip *et al.*, 2025).

The scope of this review is to provide a comprehensive synthesis of energy efficiency measures in ship design, propulsion systems, onboard energy management, operational practices, and digitalization, within the context of contemporary regulatory frameworks. It aims to highlight how design innovations, operational strategies, and data-driven tools interact synergistically to improve vessel energy performance and reduce carbon intensity. By examining both newbuild and existing vessels, the review emphasizes the importance of lifecycle approaches in energy efficiency planning. Furthermore, it considers the integration of digital technologies for real-time monitoring, predictive maintenance, and decision support to ensure continuous improvement. This review seeks to identify knowledge gaps, consolidate current best practices, and provide actionable insights for researchers, shipowners, and policymakers to accelerate energy efficiency gains in the maritime sector. Ultimately, it presents a systems-level perspective that underscores the combined potential of technical, operational, and digital strategies to advance decarbonization objectives and sustainable maritime transport.

Regulatory Framework and Energy Performance Targets

The maritime industry faces increasing pressure to reduce greenhouse gas (GHG) emissions, prompting the implementation of regulatory measures aimed at improving energy efficiency across both newbuild and existing vessels. The International Maritime Organization (IMO) has been central in establishing performance-based regulations, including the Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), and Carbon Intensity Indicator (CII), which together provide a comprehensive framework to decarbonize shipping operations (International Maritime Organization, 2026). These measures aim to reduce carbon intensity and fuel consumption while allowing flexibility in technological and operational solutions. The EEDI targets newbuild vessels by setting minimum energy efficiency levels, expressed in grams of CO₂ per ton-mile of transport work. Its phased implementation has driven innovation in hull form, propulsion systems, and auxiliary technologies, incentivizing ship designers to achieve higher efficiency without mandating specific engineering solutions (Amararitei, 2025; Talip *et al.*, 2025). Recent studies indicate that the EEDI has significantly influenced the design choices of bulk carriers, container ships, and tankers, improving fuel efficiency while maintaining operational flexibility (Talip *et al.*, 2025; Vasilev *et al.*, 2025).

To address emissions from the existing fleet, the EEXI requires vessels of 400 gross tonnage and above to calculate an attained efficiency value and demonstrate compliance with reference benchmarks derived from EEDI standards

(Amararitei, 2025; International Maritime Organization, 2026). Compliance can be achieved through technical modifications such as engine power limitation, installation of energy-saving devices, and hull or propeller retrofits, offering shipowners a range of options to meet the required performance levels (DNV, 2025). These flexible approaches have encouraged practical adoption across diverse vessel types, including container liners and tankers (Zhang *et al.*, 2024; Vasilev *et al.*, 2025). The CII complements these design- and retrofit-focused instruments by providing an annual operational rating based on actual fuel consumption relative to transport work (U.S. Department of Transportation, Maritime Administration, 2025; International Maritime Organization, 2026). Vessels are assigned a grade from A

(best) to E (worst), incentivizing operators to adopt energy-efficient practices such as speed optimization, route planning, hull maintenance, and crew training. Evidence from container liner fleets suggests that the CII has influenced operational deployment, with operators adjusting sailing speeds and voyage schedules to improve ratings while maintaining service requirements (Zhang *et al.*, 2024).

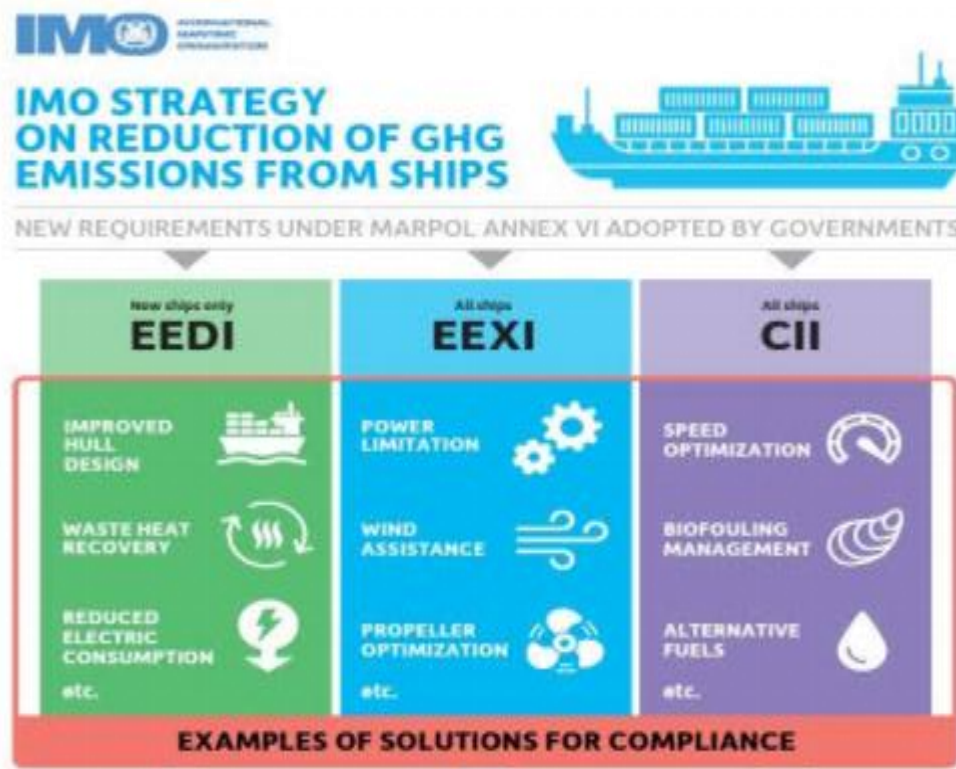


Figure 1. IMO regulatory framework. This figure illustrates the structure and key components of the regulatory system developed by the International Maritime Organization (IMO) to govern global shipping. The framework is designed to enhance maritime safety, environmental protection, and sustainable shipping operations. **Source:** Utz (2025)

Collectively, the EEDI, EEXI, and CII form a coherent, lifecycle-oriented regulatory framework that promotes energy efficiency through design, retrofit, and operational interventions. The regulations are performance-based, allowing shipowners and operators to choose the most cost-effective and context-specific solutions for compliance.

Recent research highlights that integrating these measures with digital monitoring, predictive analytics, and machine learning can further enhance energy performance and ensure continuous improvement across vessel classes (DNV, 2025; Talip *et al.*, 2025; Vasilev *et al.*, 2025). This framework establishes clear incentives for technological innovation and operational optimization, creating pathways toward a decarbonized maritime sector.

Table 1. Summary of key IMO energy efficiency regulations for ships

Instruments	Purpose	Applicability	Key metrics	Compliance
EEDI	Improve energy efficiency at design stage	Newbuilds ≥ 400 GT	g CO ₂ /t-nm	Design optimization, engines, hull and propulsion efficiency (Talip <i>et al.</i> , 2025; IMO, 2026)
EEXI	Ensure existing ships meet efficiency standards	Existing ships ≥ 400 GT	Attained vs. required EEXI	Retrofits, engine power limitation, energy-saving devices (Zhang <i>et al.</i> , 2024; Amoraritei, 2025; IMO, 2026)
CII	Evaluate operational carbon intensity	All ships ≥ 400 GT	Annual CO ₂ per transport work; A–E rating	Speed, trim, routing, maintenance; corrective action for low ratings (IMO, 2026; U.S. DOT, 2025; Vasilev <i>et al.</i> , 2025;)

Energy-Efficient Ship Design (Pre-Construction Phase)

Energy-efficient ship design is a critical component in reducing fuel consumption, greenhouse gas (GHG) emissions, and operational costs in modern maritime transport. The pre-construction phase allows naval architects to integrate hydrodynamic optimization, structural innovations, and propulsion efficiency measures, laying the foundation for compliance with the Energy Efficiency Design Index (EEDI) and future energy-performance regulations (Themelis, 2025). Central to this process is the reduction of hydrodynamic resistance, which directly affects fuel consumption and engine power requirements throughout the vessel's operational lifecycle. Hull form optimization is a primary strategy for minimizing resistance. Advanced computational tools, such as computational fluid dynamics (CFD) and multi-objective optimization techniques, enable designers to simulate complex flow phenomena, including wave-making and frictional resistance, to determine hull shapes that achieve maximal energy efficiency (Zhu *et al.*, 2024). Intelligent optimization methods, often incorporating machine learning algorithms, allow rapid exploration of multiple design parameters, balancing drag reduction with stability, displacement, and seakeeping requirements (Zhu *et al.*, 2024). Studies have shown that these approaches can reduce resistance by up to 10%, translating into significant reductions in fuel consumption over a vessel's service life (Wang *et al.*, 2025).

Energy-saving devices (ESDs) further enhance efficiency by optimizing the interaction between the hull, propeller, and surrounding flow field. Pre-ducts, stators, and wake-equalizing ducts, tailored for specific hull forms, improve propeller

inflow uniformity and reduce energy losses caused by turbulent wake structures. CFD-based simulations combined with reduced-order models demonstrate that these devices can increase propulsive efficiency by 5–12% for typical cargo vessels (Nguyen and Chandar, 2023). Tubercle-assisted propellers represent another innovation, improving thrust generation while reducing cavitation and vibration, as shown in full-scale CFD studies of large vessels (Ilter *et al.*, 2025). Propulsion integration remains essential for energy-efficient design. Optimized propeller geometries, informed by hydrodynamic modeling, enhance open-water efficiency and reduce specific fuel consumption. Integration of hull and propeller design through parametric CFD simulations enables designers to minimize interference losses and maximize overall propulsion system efficiency (Bacalja Bašić *et al.*, 2024). Additionally, predictive models allow the evaluation of trade-offs between propeller design, engine selection, and operational conditions, enabling energy savings without compromising performance.

Finally, advances in digital and data-driven design systems allow holistic evaluation of energy efficiency across multiple design domains. Integrating intelligent optimization with CFD, structural analysis, and propulsion assessment provides a comprehensive framework for early-stage design decision-making (Zhu *et al.*, 2024). These methods ensure that energy-saving strategies ranging from hull shaping and ESDs to optimized propulsion integration are systematically evaluated, producing vessels capable of high operational efficiency, regulatory compliance, and reduced environmental impact (Themelis, 2025; Wang *et al.*, 2025).

Table 2. Key energy-efficient ship design strategies in the pre-construction phase

Category	Example technology/method	Impact on efficiency
Hull Optimization	CFD-based hull shaping, multi-objective design, machine learning	Up to 10% reduction in resistance (Zhu <i>et al.</i> , 2024; Themelis, 2025; Wang <i>et al.</i> , 2025)
Energy-Saving Devices (ESDs)	Pre-ducts, stators, wake-equalizing ducts	5–12% increase in propulsive efficiency (Nguyen and Chandar, 2023)
Propulsion Enhancements	Tubercle-assisted propellers, open-water propeller optimization	3–8% improvement in propulsion efficiency (Bacalja Bašić <i>et al.</i> , 2024; Ilter <i>et al.</i> , 2025)
Digital and Data-Driven Design	Intelligent optimization frameworks, reduced-order models	Supports cumulative efficiency gains (Zhu <i>et al.</i> , 2024; Themelis, 2025)

Propulsion and Alternative Power Systems

Advances in ship propulsion and power systems are essential for decarbonising modern maritime transport and improving energy efficiency beyond incremental improvements in hull design or operational optimisation. Traditional diesel engines remain dominant in large-scale shipping, but hybrid systems, alternative fuels, and renewable energy auxiliaries are rapidly gaining traction as integrated solutions that reduce fuel consumption, lower greenhouse gas emissions, and better align vessel performance with emerging regulatory and climate targets (Zhang *et al.*, 2025; Barone *et al.*, 2026). These technologies are particularly important as the industry transitions toward low- and zero-carbon fuels and seeks to improve overall energy management under varied operating conditions. Hybrid and electric propulsion architectures combine conventional internal combustion engines with electric machines and energy storage systems, enabling flexible power distribution and improved fuel efficiency. By blending mechanical and electrical sources, hybrid systems reduce engine load variations and allow for strategic use of stored energy during low-power segments of a voyage, such as manoeuvring or port operations. Research using a dynamic programming–adaptive neuro-fuzzy inference system (DP-ANFIS) control algorithm for methanol–electric hybrid propulsion demonstrates significant potential for energy optimisation through intelligent power distribution, resulting in fuel savings and lower emissions compared with traditional systems (Li *et al.*, 2025). Similarly, broader studies on hybrid marine propulsion show that effective integration of alternative fuel capability and power limitation strategies can improve energy efficiency metrics when compared with conventional configurations, especially when combined with advanced energy management (Maloberti and Zaccone, 2025; Yuksel *et al.*, 2025). Importantly, hybrid solutions provide transitional pathways that balance operational reliability with emerging low-carbon technologies.

Complementary to hybrid architectures, the adoption of alternative fuels presents a critical strategy for reducing

carbon intensity. Liquefied natural gas (LNG), methanol, ammonia, and biofuels each offer different trade-offs in terms of energy density, emissions profiles, supply chain maturity, and infrastructure requirements. Reviews of fuel pathways show that methanol and ammonia, in particular, have strong potential for significant lifecycle emissions reductions when produced from renewable electricity, though challenges related to storage volume and safety need to be addressed (Zhang *et al.*, 2025; Barone *et al.*, 2026). Life cycle techno-economic assessments also highlight that integrating these fuels with shaft generators and dual-fuel engines can enhance energy efficiency while reducing environmental impacts, especially when renewable feedstocks are available (Tadros *et al.*, 2025). Collectively, these findings suggest that alternative fuels will play a major role in future energy-efficient propulsion, with decisions tailored to trade

routes, vessel types, and fuel availability. In addition to fuel and hybrid advances, wind-assisted propulsion systems (WAPS) have re-emerged as viable auxiliary technologies that capture renewable wind energy to supplement main engine power. Recent reviews indicate that rotor sails, kites, and rigid wing sails can deliver measurable reductions in fuel consumption on appropriate routes, particularly for long-distance voyages with consistent wind patterns (Kolodziejewski and Sosnowski, 2025). These systems can be integrated with hybrid power systems and digital controllers, allowing vessels to exploit wind energy when available while maintaining control and performance under varying weather conditions. While the initial capital cost and retrofitting complexity remain challenges for widespread adoption, several operational case studies show promising reductions in carbon intensity and fuel use.

Finally, energy management strategies that coordinate hybrid power sources, alternative fuels, and operational controls are increasingly recognised as important drivers of overall system efficiency. Sophisticated energy management systems, incorporating predictive algorithms and real-time monitoring, allow vessels to optimise power dispatch among engines,

batteries, and renewable auxiliaries. These strategies can reduce peak load requirements, minimise wasted fuel, and leverage stored energy more effectively, resulting in measurable gains in energy efficiency and reduced operational emissions (Maloberti and Zaccone, 2025). As digitalisation and sensor networks continue to proliferate in the maritime domain, their integration with propulsion and power systems will further strengthen energy performance and support the transition to sustainable shipping.

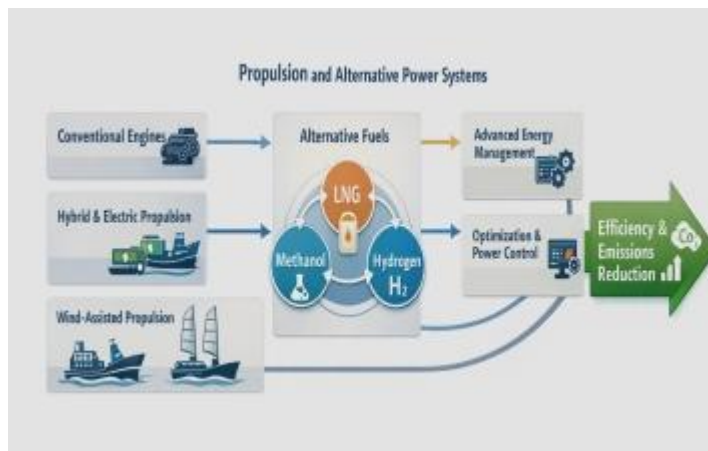


Figure 2. Integrated propulsion and alternative power systems for energy-efficient shipping. The schematic shows the interaction of hybrid-electric propulsion, alternative fuels (LNG, methanol, hydrogen, ammonia), wind-assisted systems, and energy management strategies to optimize ship energy efficiency and reduce emissions.

Sources: Modified from Kolodziejcki and Sosnowski (2025); Li *et al.* (2025)

Onboard Energy Management and System Optimization

Onboard energy management and system optimization represent a critical pillar of maritime decarbonization, enabling ships to maximize energy utilization while complying with increasingly stringent regulatory frameworks. Modern vessels operate as integrated energy systems in which propulsion, auxiliary loads, thermal systems, and power generation units interact dynamically (Pan *et al.*, 2025). Effective coordination of these subsystems reduces fuel consumption, lowers emissions, and improves compliance with Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII) requirements. Advanced optimization frameworks combining data-driven prediction and thermodynamic recovery systems have demonstrated measurable reductions in carbon emissions when aligned with regulatory metrics (Pan *et al.*, 2025). Such integrated strategies reflect a shift from isolated component improvements toward holistic energy performance management. A major contributor to onboard efficiency enhancement is waste heat utilization, which captures thermal energy from exhaust gases, jacket cooling water, and auxiliary machinery for productive reuse. Comprehensive analyses

indicate that optimized waste heat recovery (WHR) systems significantly increase overall plant efficiency by converting otherwise dissipated heat into useful electrical or thermal output (Miller *et al.*, 2024). Beyond conventional power augmentation, WHR integration with advanced control architectures further improves system stability and load balancing. Extending this concept, waste heat recovery has also been successfully applied to seawater desalination processes, improving freshwater production efficiency while simultaneously reducing environmental impact and lifecycle operational costs (Towhid *et al.*, 2025). These findings confirm that WHR technologies provide multidimensional benefits across energy, environmental, and operational domains.

Another high-impact domain is the optimization of HVAC (heating, ventilation, and air conditioning) systems, which account for a substantial portion of hotel load consumption, particularly in passenger and cruise vessels. Digital twin frameworks have emerged as powerful tools for real-time monitoring, predictive simulation, and adaptive control of onboard HVAC systems. Through dynamic modeling and performance feedback, digital twins enable fine-tuned regulation of airflow, temperature, and compressor loads, leading to measurable efficiency gains and reduced emissions (Barone *et al.*, 2025). This approach enhances not only energy performance but also onboard comfort and system reliability, reinforcing the value of cyber-physical integration in maritime energy management. Complementing thermal and auxiliary optimizations, real-time hybrid control of onboard power networks has become increasingly essential in vessels equipped with energy storage systems and multiple generation sources (Vu *et al.*, 2024). Intelligent load shedding, predictive dispatch strategies, and storage coordination enable resilient and energy-efficient power system operation under fluctuating demand conditions. Real-time hybrid control frameworks integrating storage management and adaptive load control have demonstrated improved operational efficiency and enhanced power system stability in integrated shipboard energy systems (Vu *et al.*, 2024). These approaches support seamless interaction between propulsion, auxiliary loads, and storage units, reducing peak fuel consumption and enhancing overall system robustness.

Collectively, onboard energy management strategies—spanning predictive emission modeling, waste heat recovery, desalination integration, HVAC digital twin optimization, and hybrid power control illustrate the transition toward fully integrated maritime energy systems. By combining thermodynamic recovery technologies with advanced data-driven control architectures, modern vessels can achieve substantial efficiency improvements while ensuring regulatory compliance and operational reliability. These developments position onboard energy optimization not merely as a supplementary measure but as a central mechanism for sustainable and high-performance shipping operations.



Figure 3. Integrated onboard energy management architecture for maritime energy efficiency enhancement. The schematic illustrates the integration of propulsion, waste heat recovery (WHR), WHR-based desalination, HVAC digital twin optimization, energy storage, and real-time energy management systems (EMS). Arrows represent energy and control flows coordinated to improve efficiency, reduce emissions, and enhance regulatory compliance.

Sources: Miller *et al.* (2024); Barone *et al.* (2025)

Operational Energy Efficiency Measures

Operational energy efficiency measures represent some of the most immediate and cost-effective pathways for reducing fuel consumption and greenhouse gas emissions in the maritime sector. Unlike capital-intensive retrofits or alternative fuel transitions, operational strategies focus on optimizing vessel speed, routing, loading conditions, and port coordination to improve real-time performance. These measures have been identified as high-potential interventions capable of delivering substantial emission reductions while supporting compliance with evolving decarbonization targets (DNV, 2025; Fadaie *et al.*, 2025). As the shipping industry faces increasing pressure to align with net-zero ambitions, operational optimization is emerging as a critical transitional mechanism (Early, 2025).

Slow Steaming and Speed Optimization

Slow steaming remains one of the most widely implemented operational strategies for fuel and emission reduction. By reducing sailing speed below design service speed, ships achieve disproportionate fuel savings due to the nonlinear relationship between speed and propulsion power demand. Empirical analyses of slow steaming and Just-In-Time (JIT) strategies demonstrate measurable reductions in fuel consumption and carbon intensity, although impacts vary across vessel types and trade routes (Menelaou *et al.*, 2026). When combined with meteorological data and port

coordination, dynamic speed optimization further enhances efficiency by minimizing unnecessary acceleration and idle time (Liu *et al.*, 2026).

Weather Routing and Voyage Optimization

Weather routing and voyage optimization leverage environmental data including wind, waves, and tidal currents—to identify energetically favorable routes. The integration of tidal current information into route planning has been shown to improve propulsion efficiency by reducing resistance and optimizing transit paths in coastal waters (Yang and Byun, 2024). Advanced routing algorithms that incorporate meteorological forecasting can further support JIT arrival strategies, reducing both fuel consumption and emissions during long-haul operations (Liu *et al.*, 2026). Such digital voyage optimization tools contribute directly to operational carbon intensity improvements.

Trim and Ballast Optimization

Optimizing trim and ballast conditions reduces hydrodynamic resistance by aligning hull geometry with favorable flow characteristics. Even minor adjustments in longitudinal trim can produce measurable reductions in fuel consumption, particularly for bulk carriers and container vessels. Operational guidance frameworks emphasize trim optimization as a low-cost, high-impact measure within broader energy management strategies (DNV, 2025). Systematic assessments of operational measures confirm that trim and ballast adjustments can contribute incrementally to cumulative emission reductions across fleet operations (Fadaie *et al.*, 2025).

Hull and Propeller Maintenance Strategies

Hull fouling and propeller surface degradation significantly increase frictional resistance, leading to higher fuel consumption. Regular underwater cleaning, propeller polishing, and condition-based maintenance reduce drag and restore propulsion efficiency. Reviews of decarbonization technologies identify hull and propeller maintenance as essential operational measures capable of delivering consistent efficiency gains with relatively low implementation barriers (Fadaie *et al.*, 2025). These maintenance strategies are particularly important for maintaining performance stability under stricter carbon intensity regulations (DNV, 2025).

Just-In-Time (JIT) Port Arrival Systems

Just-In-Time port arrival systems align vessel speed with berth availability, minimizing anchorage waiting time and associated fuel waste. Coordinated speed management reduces unnecessary fuel burn and enhances supply chain efficiency. Empirical analyses of JIT implementation indicate improved voyage efficiency and carbon intensity performance when port-vessel communication systems are effectively integrated

(Menelaou *et al.*, 2026). Dynamic optimization models incorporating meteorological conditions and port scheduling further strengthen JIT effectiveness (Liu *et al.*, 2026). As the industry seeks scalable pathways toward net-zero emissions, JIT systems represent a practical and immediately deployable solution (Early, 2025). Collectively, slow steaming, voyage optimization, trim adjustment, proactive maintenance, and JIT

coordination demonstrate how operational intelligence can deliver meaningful efficiency gains. While these measures alone cannot achieve full decarbonization, they constitute an essential short- to medium-term strategy within the broader maritime energy transition (Sakalayan *et al.*, 2026).

Table 3. Operational energy efficiency measures and their decarbonization mechanisms in maritime transport

Operational measure	Core mechanism	Energy / Emission Reduction Pathway	Digital/ technical enablers	Implementation enabler
Slow Steaming and Speed Optimization	Reduction of vessel speed below design speed	Lower propulsion power demand (\propto speed ³ relationship); reduced fuel consumption and CO ₂ emissions	AI-based speed optimization models; real-time performance monitoring	Schedule reliability, charter-party constraints, market freight volatility
Weather Routing and Voyage Optimization	Route and speed adjustments based on meteorological and oceanographic data	Avoidance of adverse weather; reduced resistance and fuel use	Satellite weather data; predictive routing algorithms; machine learning forecasting	Data reliability, onboard decision autonomy, crew training
Trim and Ballast Optimization	Dynamic adjustment of vessel trim and ballast for minimum resistance	Reduced hydrodynamic drag; optimized propeller efficiency	Onboard trim optimization software; sensor-based stability monitoring	Stability limits, cargo distribution constraints
Hull and Propeller Maintenance Strategies	Regular cleaning and surface condition management	Prevention of biofouling-induced drag increase; maintained propulsion efficiency	Condition monitoring systems; performance analytics	Dry-docking schedules, coating lifecycle costs
Just-In-Time (JIT) Port Arrival Systems	Synchronization of arrival time with berth availability	Elimination of anchorage waiting; optimized speed profiles; reduced auxiliary fuel use	Port-ship data integration platforms; AIS-based coordination systems	Port digitalization level, stakeholder coordination, contractual frameworks

Challenges, Research Gaps, and Future Directions

Achieving deep decarbonization in maritime transport requires overcoming structural, technological, operational, and institutional barriers. A comprehensive synthesis of decarbonization technologies shows that while numerous technical and operational measures exist, ranging from energy-efficiency improvements to alternative fuels, their emission reduction potentials vary widely, and no single solution can independently deliver net-zero targets (Fadaie *et al.*, 2025). The challenge therefore lies in integrated deployment, lifecycle assessment consistency, and system-level coordination across vessel types and trade routes. A critical gap concerns the alignment between operational measures and logistics realities. Although strategies such as slow steaming and Just-In-Time (JIT) arrival can significantly

reduce fuel consumption, their effectiveness depends on segment-specific characteristics, market volatility, and contractual structures. Empirical evidence indicates that dry bulk and tramp shipping markets face unique constraints that may limit uniform application of these strategies (Menelaou *et al.*, 2026). This highlights the need for adaptive, segment-specific operational frameworks rather than generalized policy prescriptions.

Technological innovation continues to accelerate, including digital twins, advanced propulsion systems, hybrid power architectures, and data-driven optimization tools. However, adoption is constrained by capital intensity, technological maturity gaps, regulatory uncertainty, and stakeholder coordination challenges (Alamouh and Ölçer, 2025). A bibliometric assessment of maritime decarbonization research

further reveals fragmentation across disciplines and insufficient cross-sector integration between engineering, economics, and policy research (Anantharaman *et al.*, 2025). Future research must therefore prioritize interdisciplinary modelling approaches and harmonized evaluation metrics. Ports represent another systemic bottleneck in achieving maritime net-zero ambitions. Decarbonization requires electrification of port operations, alternative fuel bunkering infrastructure, and coordinated energy supply chains. Yet ports face financial constraints, governance complexity, and uneven technological readiness, which may delay large-scale implementation (Halpe *et al.*, 2025). Stronger port–ship integration and collaborative investment frameworks are essential to prevent infrastructure from becoming a transition barrier.

From a technical performance perspective, emerging studies emphasize the importance of data-driven optimization. For example, hull-fouling management using predictive cleaning schedules demonstrates measurable carbon footprint reductions through improved hydrodynamic efficiency (Ward *et al.*, 2026). Similarly, stochastic models for dynamic Carbon Intensity Indicator (CII) management highlight the complexity of maintaining compliance under uncertain market and operational conditions (Cheng *et al.*, 2025). These findings suggest that future decarbonization pathways will increasingly depend on real-time analytics, predictive modelling, and integrated performance monitoring systems.

Conclusion

Improving energy efficiency in maritime transport requires a coordinated integration of technological innovation, operational optimization, regulatory alignment, and digital intelligence. While significant progress has been achieved through design improvements, waste heat recovery, advanced propulsion systems, and data-driven operational strategies, no single solution can independently deliver deep decarbonization. Instead, system-level integration across vessels, ports, and supply chains is essential. Operational measures such as speed optimization, weather routing, trim management, and Just-In-Time arrivals offer immediate and cost-effective emission reductions, while emerging digital tools enhance monitoring, predictive control, and regulatory compliance. At the same time, infrastructure readiness, investment capacity, and market dynamics remain critical constraints that shape the pace and scale of implementation. The pathway toward sustainable maritime transport therefore depends on multi-layered strategies that combine short-term efficiency gains with long-term structural transformation. Strengthening collaboration among shipowners, ports, regulators, technology providers, and researchers will be central to achieving resilient, scalable, and economically viable decarbonization across the global fleet.

Acknowledgement

We thank all the researchers who contributed to the success of this research work.

Conflict of Interest

The authors declared that there are no conflicts of interest.

Funding

No funding was received for this research work.

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How to cite this article

Paul-Okore, R. O., Adondua Abah, M., Abimbola Oladosu, M., Nengimote Godwin, M., Evans Joel, U., Azeez Akinwumi, F., Olasunkanmi, J., & Dominic Agida, O. (2026). Energy efficiency measures in ship design and operation. *Chemical and Environmental Science Archives*, 6(2), 12–22. <https://doi.org/10.47587/CESA.2026.6201>

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