# FUEL EFFICIENCY AND EMISSIONS REDUCTION IN THE SHIPPING INDUSTRY

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# NTRODUCTION

The maritime industry serves as the backbone of global trade, facilitating the transport of approximately 90% of the world's goods. Beyond its economic significance, the sector plays a crucial role in environmental stability due to its energy consumption patterns and related emissions. The ongoing global climate crisis is closely linked to energy production and consumption, with fossil fuel dependence being a primary source of greenhouse gas (GHG) emissions. According to the International Maritime Organization (IMO) 2020 report, the shipping sector accounts for approximately 2.89% of global carbon dioxide ($CO_2$) emissions—surpassing the emissions of some individual countries. Consequently, improving fuel efficiency and reducing emissions in shipping is not only an environmental imperative but also a regulatory requirement. Technological advancements aimed at enhancing energy efficiency and adopting alternative fuels offer significant opportunities to improve the environmental performance of the industry. In this regard, the IMO's mandatory Energy Efficiency Design Index (EEDI) measures the energy efficiency of new ship designs by

calculating $CO_2$ emissions per unit of transport work, thereby encouraging the construction of vessels with reduced carbon intensity. This regulation aligns shipbuilding processes with sustainability goals. This study focuses on the relationship between ship engine revolutions per minute (RPM), fuel consumption, energy efficiency, and greenhouse gas emissions.

Engine RPM is a fundamental determinant of fuel consumption and, subsequently, emission levels. Within this context, the compatibility and coordination of ship agencies and brokers with this process play a vital role in enhancing operational efficiency and environmental performance. Ship agencies and brokers ensure the smooth and effective management of operations, providing critical support for the optimization of energy use and implementation of emission reduction strategies.

# GLOBAL SHIPPING INDUSTRY AND EMISSIONS

International maritime transport is an important source of greenhouse gas emissions, contributing notably to global climate change. According to the International Maritime Organization's Fourth Greenhouse Gas Study, shipping emitted approximately 1,056 million tonnes of $CO_2$ in 2018, accounting for about 2.89% of total global anthropogenic $CO_2$ emissions that year (IMO, 2020). Projections state that, without additional mitigation measures, emissions from the sector could rise by up to 50% by 2050 compared to 2018 levels (CE Delft, 2020).

Large container vessels and bulk carriers, due to their substantial engine power requirements, are major contributors to $CO_2$ and nitrogen oxides ($NO_x$) emissions. The widespread use of heavy fuel oils (HFO), which possess high energy density however poor environmental profiles, further exacerbates this matter. Thus, reducing emissions have need of fuel switching and improvements in engine efficiency.

When we examine the energy Efficiency Design Index (EEDI) and Its Role in Maritime Decarbonization, it should be highlighted that the International Maritime Organization introduced the Energy Efficiency Design Index, in other words EEDI in 2013 as a mandatory regulation aimed at improving the energy efficiency of newly built vessels. As the first global climate-related standard for any transport sector, the EEDI illustrates a crucial step toward reducing greenhouse gas emissions from international shipping. It quantifies a vessel's carbon dioxide ($CO_2$) emissions per tonne-mile of transport work and sets a maximum limit that progressively tightens over time. This regulatory pressure has pushed innovation across the maritime industry, compelling ship designers and manufacturers to pursue more sustainable and energy-efficient solutions.

For example, from 2025 onward, new container ships must achieve at least a 30% reduction in $CO_2$ emissions compared to the 2000–2010 baseline (IMO, 2020b). In response, the industry has adopted a variety of advanced Technologies with lightweight composite materials, optimized hull and propeller designs, and low-RPM, high-efficiency engines. These measures not only drop emissions but also enhance fuel economy, yielding both environmental and operational benefits.

The EEDI has proven to be more than just a compliance mechanism, it serves as a catalyst for innovation in ship design. By enforcing performance-based targets rather than prescriptive technology mandates, the regulation authorises flexibility in how shipowners meet emission thresholds. This approach fosters technological diversity and encourages investment in R&D tailored to specific vessel types and trade routes.

On the other hand, the regulation primarily enforces to newbuild ships, meaning a vast number of existing vessels are not directly affected. To address this gap, the IMO has introduced complementary measures such as the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII), which target operational efficiency for the global fleet.

Despite its limitations, the EEDI remains a cornerstone of the IMO's broader decarbonization strategy, which includes decreasing total GHG emissions from shipping by at least 50% by 2050 compared to 2008 levels (IMO, 2018). As such, EEDI not only shapes the technical trajectory of the maritime industry but also reinforces the alignment of shipping with global climate goals.

While the Energy Efficiency Design Index remains a substance of global decarbonization efforts guided by the International Maritime Organization, regional policies and market-based mechanisms are increasingly critical in accelerating its affect. Among these, the European Union has positioned itself as a pioneer in maritime climate governance by integrating complementary regulatory tools that reinforce EEDI goals.

As of January 2024, the European Union has formally included maritime transport within its Emissions Trading System. This policy is to require shipping companies to purchase emissions allowances for every tonne of carbon dioxide emitted by vessels operating within EU waters or making calls to EU ports. By assigning a monetary value to $CO_2$ emissions, the system creates direct economic incentives for shipowners to invest in low-emission technologies and EEDI-compliant vessel designs (European Commission, 2023; EMSA, 2024). The higher the ship's energy efficiency, the fewer emissions it produces, and consequently, the lower its compliance cost under the ETS.

Furthermore, many European port managements are implementing positive reinforcement strategies to reward environmental performance. Vessels with favourable EEDI ratings or overall lower emissions may receive discounts and to have low costs. For example, some the ports offer incentive programs based on a ship's Environmental Ship Index (ESI) score or other sustainability metrics, which often correlate with EEDI compliance (Port of Rotterdam, 2023; Green Award Foundation, 2023).

These initiatives are cantilevered by wider industry programs. These initiatives ensure standardized frameworks for measuring and recognizing ship-level environmental performance. Though voluntary, these schemes have acquired traction across Europe and parts of Asia and align closely with the objectives of the EEDI by supporting energy efficiency and emissions transparency (Green Award, 2023).

Through such regional measures, the European Union and its maritime stakeholders are effectively extending the influence of EEDI from the design phase into active vessel operation. While the IMO assures the global regulatory baseline, regional mechanisms like the EU ETS and port-based incentives translate policy into tangible economic and environmental results—encouraging continuous innovation and accelerating the transition to low-carbon shipping.

## FUEL TYPES AND CARBON INTENSITY

The widespread reliance on Heavy Fuel Oil (HFO), Marine Diesel Oil (MDO), and Marine Gas Oil (MGO) is rooted in historical cost efficiency and high energy content. But, these fuels present important environmental drawbacks, especially HFO, which contains high levels of sulphur and heavy metals. The use of heavy fuel oil ensues in substantial $SO_x$ and PM emissions, contributing to both air pollution and acidification in marine ecosystems.

In addition, MDO and MGO are still fossil-based and contribute to substantial $CO_2$ emissions. The International Maritime Organization's IMO 2020 regulation, which limits sulphur content in marine fuel to 0.5% m/m globally, has pushed many shipowners to switch to low sulphur alternatives, install exhaust gas cleaning systems (scrubbers), or consider alternative fuels (IMO, 2020). As a result, conventional fuels present short-term operational familiarity and infrastructure support but are incompatible with long-term climate targets.

Carbon intensity, measured in kilograms of $CO_2$ emitted per kilogram of fuel burned, serves as a key indicator for comparing the environmental impact of marine fuels. It should be emphasized that the overall greenhouse gas affect also depends on other pollutants such as methane, nitrogen oxides ($NO_x$), and particulate matter (PM), which can substantially impact the total emissions profile. Therefore, carbon intensity seems as a key driver in regulatory compliance (e.g., EEDI, EEXI, and CII) and investment decisions. In conclusion, carbon intensity has an important factor for comparative analysis, but it must be contextualized within broader lifecycle and operational frameworks.

Several low- and zero-carbon fuels are under consideration to reduce maritime emissions. Liquefied Natural Gas is the most widely adopted transitional fuel but is limited by methane slip, which undermines its $CO_2$ reduction benefits due to methane's high Global Warming Potential (Faber et al., 2018).

Biofuels offer compatibility with existing engines however face sustainability challenges and scalability constraints, with lifecycle emissions varying significantly by feedstock and production method (Corbett et al., 2020). Hydrogen and ammonia are zero-carbon fuels when produced renewably; however, their deployment is restricted by safety concerns, $NO_x$ emissions from ammonia combustion, and insufficient bunkering infrastructure (Bicer et al., 2020). Methanol provides a practical alternative, with easier storage and handling than hydrogen or ammonia, and can operate in dual-fuel engines. Its environmental benefits, however, depend heavily on production pathways (Mekhilef et al., 2012).

Therefore, alternative fuels present viable decarbonization routes but remain constrained by technological maturity, safety issues, and economic feasibility.

When we examined the fuel properties, engine design, and propulsion efficiency, we found that the relationship between fuel characteristics and engine operation is primary to optimizing propulsion efficiency and decreasing emissions in maritime vessels. Each fuel has distinct combustion properties—such as energy density, volatility, and ignition behaviour—that require tailored engine designs and operating parameters.
For instance, engines powered by Liquefied Natural Gas typically operate at lower RPMs and require optimized injection timing to maximize combustion efficiency and minimize methane slip. Alternative fuels such as biofuels, methanol, hydrogen, and ammonia further complicate engine performance by affecting thermal efficiency and emission profiles. These variations necessitate adaptive engine technologies, advanced after-treatment systems, and precise operational strategies to fully leverage their environmental benefits. In this context, RPM optimization is important. For instance, LNG-fuelled engines must balance lower optimal RPM ranges with voyage speed and emission reduction targets. Digital engine monitoring and control systems has a significant role in sustaining compliance and enhancing efficiency across varying operational conditions.

Fuel choice affects not only emissions but also the vessel's propulsion dynamics and overall efficiency. This integrated perspective is fundamental to acquiring significant emission reductions while ensuring economic and operational viability.

The key priorities must encompass a comprehensive assessment of lifecycle environmental impacts, ensure optimal compatibility between fuels, engines, and operations, address regional regulatory differences such as the EU Emissions Trading System (ETS), and align industry initiatives with the IMO's objective of cutting greenhouse gas emissions by 50% by 2050.

Achieving a sustainable maritime future requires collaboration not only among shipbuilders, engine manufacturers, fuel suppliers, regulators, and operators but also with ship agencies and brokers. These intermediaries are vital in guiding shipowners through fuel selection, regulatory compliance, and operational optimization amid evolving environmental standards.

Given the complexity and diversity of fuels and technologies, a flexible, data-driven approach supported by digitalization is essential for maximizing vessel performance and meeting regulatory requirements. Ship brokers and agencies, positioned at the nexus of market knowledge and operational execution, offer critical support by advising on fuel availability, chartering options, and compliance strategies, enabling shipowners to navigate the transition efficiently. The shift toward diverse, tailored fuel solutions aligned with vessel types and trade routes demands adaptability and innovation. While integrated research, strong policy frameworks, and market incentives remain fundamental, the active engagement of brokers and agencies is key to accelerating the maritime sector's decarbonization by bridging technical, commercial, and regulatory aspects.

## OVERVIEW OF MARINE ENGINE TYPES

Marine propulsion relies primarily on two-stroke and four-stroke diesel engines, each exhibiting distinct operational and environmental characteristics that critically influence fuel efficiency and emissions. Two-stroke engines, favoured in large ocean-going vessels due to their ability to deliver continuous power at low speeds, benefit from high torque and fuel efficiency on long voyages. Their large cylinder diameters and slower RPM optimize combustion, resulting in lower specific fuel consumption (Wang, Corbett, & Firestone, 2017). However, the traditional scavenging process in two-stroke engines leads to higher methane slip and particulate matter emissions.

In contrast, four-stroke engines, commonly used in smaller vessels and auxiliary power units, operate at higher speeds and provide greater flexibility in power output and fuel options, including alternative fuels like LNG and biofuels. Their precise combustion control allows for lower $NO_x$ and particulate emissions, often enhanced by technologies such as exhaust gas recirculation (EGR) and diesel particulate filters (ICCT, 2020).

Engine RPM is a pivotal factor influencing combustion efficiency and emissions. Both engine types have an optimal RPM range where specific fuel consumption is minimized; operating outside this range increases incomplete combustion and frictional losses, thereby escalating fuel consumption and emissions (Wang et al., 2017). Modern engine management systems that adjust injection timing, turbocharging, and exhaust gas recirculation in real time are essential to maintain operation within these optimal ranges, maximizing thermal efficiency and emission control (IMO, 2019).

From a regulatory perspective, the Energy Efficiency Design Index (EEDI) incentivizes the adoption of engines and technologies that reduce $CO_2$ emissions per transport work unit. Two-stroke engines, with their inherently high efficiency at low RPMs, can achieve favourable EEDI scores, especially when paired with low-carbon fuels. Yet, to meet increasingly stringent standards, optimization of engine RPM and advanced emission control systems are imperative (IMO, 2019). Four-stroke engines, while more adaptable in fuel types and suitable for smaller vessels, typically operate at higher RPMs resulting in greater fuel consumption per power unit, posing challenges for EEDI compliance (ICCT, 2020).
Maintaining precise RPM management through sophisticated control systems is therefore critical across engine types to align operational performance with regulatory targets (Smith et al., 2014).

## IN-DEPTH ANALYSIS OF RPM OPTIMIZATION IMPACT

Engine speed (RPM) is a crucial parameter that significantly affects marine engine performance, fuel consumption, and emission profiles. This section provides a comprehensive examination of how optimizing RPM influences thermodynamic efficiency, fuel consumption models, emission generation, and regulatory compliance metrics such as the Energy Efficiency Design Index (EEDI).

Marine engines exhibit peak thermodynamic efficiency within a specific RPM range. As RPM increases, the combustion duration shortens, which can lead to incomplete combustion, thereby increasing emissions such as CO, unburned hydrocarbons, and particulate matter. Simultaneously, mechanical losses due to friction and moving parts rise, which further escalates fuel consumption (Zhou & Fang, 2019). Conversely, operating at very low RPM results in increased engine load and unstable combustion, leading to reduced efficiency (Wang et al., 2017). These findings highlight the critical importance of maintaining engine RPM within an optimal range to balance fuel efficiency and emissions control.

Specific fuel consumption typically measured in grams per kWh, directly correlates with engine RPM. Specific fuel consumption reaches its minimum at the engine’s optimal RPM, representing peak efficiency. Deviations above this optimal speed, for instance a 10% increase in RPM, can result in a 5–8% increase in fuel consumption (Wang et al., 2017). Furthermore, engine load combined with RPM changes heavily influences combustion efficiency; for example, running at high RPM under low load conditions causes inefficient fuel use (ICCT, 2020). These dynamics underscore RPM’s pivotal role in accurate fuel consumption modelling and optimization.

Variations in engine RPM significantly impact the generation of harmful emissions, particularly nitrogen oxides ($NO_x$) and particulate matter (PM). Higher RPMs elevate combustion temperatures, accelerating $NO_x$ formation (Høyer & Skaarup, 2021). In contrast, lower RPMs may cause incomplete combustion, resulting in increased particulate emissions. Optimal RPM management improves the effectiveness of emission control technologies such as Selective Catalytic Reduction and Exhaust Gas Recirculation (EGR), which rely on stable combustion conditions for maximum efficiency (IMO, 2019).

The Energy Efficiency Design Index (EEDI) relies heavily on engine performance metrics, which are sensitive to RPM variations. Operating engines at low RPM and load conditions increases specific energy consumption, thereby raising the EEDI score. Conversely, RPM optimization reduces energy use and improves EEDI ratings (Smith et al., 2014). Achieving compliance with EEDI standards also necessitates integrating alternative fuels and advanced technologies, making RPM tuning an integral part of a multifaceted efficiency strategy (IMO, 2019).

Optimizing engine RPM is essential for advancing fuel efficiency and reducing environmental impact in maritime operations. Maintaining engine speeds within the thermodynamically optimal range minimizes fuel consumption and emissions simultaneously. However, striking this balance is a complex engineering challenge since excessively high RPMs increase harmful emissions, while very low RPMs degrade fuel efficiency. Modern engine control systems play a vital role in this context, providing real-time adjustments to fuel injection timing, turbocharging, and exhaust gas recirculation to ensure optimal combustion.

Furthermore, evolving regulatory frameworks such as IMO’s EEDI push for integrated solutions that consider not only engine speed but also fuel type, emission control technologies, and operational strategies. This holistic approach is key to achieving sustainable maritime operations. Therefore, RPM optimization is a fundamental technical lever in the transition to greener shipping. Advances in digitalization and AI-driven engine management are expected to further enhance these gains, maximizing both environmental benefits and operational cost savings.

In the light of the above information, it demonstrates the critical role of RPM optimization in reducing fuel consumption and emissions. Coupling engine operational strategies with advanced emission control technologies ensures compliance with evolving regulations and supports sustainable shipping practices.

# IMPACT OF EU MRV REGULATIONS AND IMO SUPPORT ON SHIPPING AGENTS/ SHIP BROKERS

The European Union's active support of the International Maritime Organization (IMO) as the key regulator of emissions from the international shipping sector—and the proposal of EU-wide Monitoring, Reporting, and Verification (MRV) regulations—significantly influences the roles of shipping agents and ship brokers within the maritime industry.

Shipping agents and brokers act as vital intermediaries, guiding shipowners and operators through the complex process of complying with MRV regulations. Given that MRV requires systematic data collection and transparent reporting of vessel emissions, agents can provide essential support by managing data flows, ensuring accurate documentation, and facilitating adherence to evolving legal frameworks.

Agents have a key role in optimizing port and voyage operations to improve fuel efficiency. Brokers, meanwhile, can advise shipowners on adopting new fuel-saving technologies and operational strategies—such as speed optimization—that reduce emissions and operating costs. This operational consultancy aligns closely with the EU and IMO's goals to promote energy-efficient shipping.

Compliance with MRV and IMO regulations offers shipowners a reputational edge in a market increasingly valuing environmental responsibility. Shipping agents and brokers help their clients leverage this advantage by enabling transparent emissions reporting and by facilitating the adoption of greener practices, thus enhancing market access and client relationships.

Transparent emissions reporting supports financial institutions and investors in evaluating environmental risks associated with shipping assets. Agents and brokers play a critical role by ensuring timely and accurate emission data, which can improve clients' access to green financing, favourable loan terms, and investment opportunities aligned with sustainability criteria.

As a result, the EU's MRV regulation and IMO's emission frameworks expand the scope and importance of shipping agents and ship brokers as compliance facilitators, operational efficiency consultants, market enhancers, and financial risk managers. These developments elevate their strategic role in driving environmental performance and sustainability in the shipping sector.

# CONCLUSION

This study clearly demonstrates that optimizing marine engine revolutions per minute (RPM) is essential for reducing fuel consumption and lowering greenhouse gas emissions in the shipping industry. Maintaining engine RPM within an optimal range improves combustion efficiency, reduces fuel waste, and minimizes harmful emissions such as nitrogen oxides and particulate matter. These improvements help ships comply with international regulations like the Energy Efficiency Design Index (EEDI) and also reduce operational costs through better fuel economy.

However, RPM optimization alone is not enough. Effective emission reduction requires a combined approach that includes choosing the right fuel type, applying advanced engine technologies, and implementing real-time engine management systems. These factors work together to maximize energy efficiency and minimize environmental impact during vessel operations.

Ship agencies and brokers play a crucial role in this process by supporting shipowners in navigating complex technical, commercial, and regulatory challenges. They use decision-making tools such as the Analytic Hierarchy Process (AHP) to evaluate and balance different factors, including engine RPM, fuel types, emission limits, costs, and operational needs to find the best solutions tailored to each vessel and trade route.

By applying structured decision methods like AHP, agencies and brokers provide clear, data-driven advice that helps optimize ship performance and meet environmental goals. Their expertise ensures that ships not only comply with regulations but also operate efficiently and economically.

In summary, optimizing engine RPM is a key technical step toward greener shipping, but its success depends on coordinated action across technology, operations, and strategy. Ship agencies and brokers are vital partners in this effort, bridging the gap between technical innovations and real-world operations. Their involvement accelerates the shipping industry's transition to sustainability, supporting global climate targets and securing a more efficient, low-emission future for maritime transport

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