






Review

Operational Decarbonization Strategies for Maritime Vessels: Power Limitation Technologies and Alternative Fuels

Olga Petrychenko ^{1,*}, Tymur Stoliaryk ¹, Sergey Goolak ², Maksym Levinskyi ³, Vaidas Lukoševičius ^{4,*}, Robertas Keršys ⁴ and Artūras Keršys ⁴

¹ Ship's Handling Department, National University 'Odessa Maritime Academy', Didrikhson Str. 8, 65052 Odessa, Ukraine; tymur.st@gmail.com

² Department of Electromechanics and Rolling Stock of Railways, National Transport University, M. Omelianovycha-Pavlenka Str. 1, 01010 Kyiv, Ukraine; s.hulak@ntu.edu.ua

³ Theory of Automatic Control and Information Technologies Department, National University 'Odessa Maritime Academy', Didrikhson Str. 8, 65052 Odessa, Ukraine; maxlevinskyi@gmail.com

⁴ Department of Transport Engineering, Faculty of Mechanical Engineering and Design, Kaunas University of Technology, Studentų Str. 56, 44249 Kaunas, Lithuania; robertas.kersys@ktu.lt (R.K.); arturas.kersys@ktu.lt (A.K.)

* Correspondence: o.petrychenko@onma.edu.ua (O.P.); vaidas.lukosevicius@ktu.lt (V.L.)

Abstract

This article addresses the operational challenges facing maritime vessels in the context of decarbonization, with a focus on developing staged recommendations for the integration of power limitation systems and alternative fuels. The systematisation of existing decarbonization problems in the maritime sector and the establishment of their interrelationships constitute the framework for developing coherent decarbonization strategies for the industry. The analysis of alternative fuels identifies the key factors that drive fuel selection in practice. The analysis of contemporary energy consumption regulation technologies has shown that power limitation systems operating through controllable pitch propellers (CPP), integrated with electronic remote-control systems, provide the highest flexibility in managing propulsion characteristics without altering engine rotational speed. The comparative analysis of the engine power limitation (EPL) and shaft power limitation (SHaPoLi) systems has confirmed that SHaPoLi offers a greater potential for reducing fuel consumption and carbon dioxide (CO₂) emissions; however, it comes at higher capital expenditure at the implementation stage. Pairing power limitation with alternative fuels shows that deep cuts in the sector's carbon footprint are within reach. The economic analysis of power limitation system deployment has revealed the potential for achieving considerable operational cost savings, with a balanced consideration of capital investments and operational benefits. Future research should target the optimisation of EPL and SHaPoLi systems and their integration with other energy-saving technologies. Transitioning to alternative fuels in parallel offers the greatest cumulative reduction in the sector's carbon footprint.



Academic Editor: Corrado Rindone

Received: 31 March 2026

Revised: 6 May 2026

Accepted: 12 May 2026

Published: 14 May 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article

distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: maritime decarbonization; engine power limitation; shaft power limitation; alternative marine fuels; energy efficiency existing ship index (EEXI) compliance; carbon intensity; sustainable

1. Introduction

Maritime transport carries over 80% of global cargo by volume and contributes approximately 2–3% of global CO₂ emissions, along with significant volumes of SO_x, NO_x,

and particulate matter [1–4]. In 2018, shipping emitted 940 million tonnes of CO₂ alone [5]. Tightening IMO regulations—including MEPC.335(76), MEPC.375(80), EEDI, SEEMP, EEXI, and CII—are compelling operators to pursue engine and shaft power optimisation via EPL and SHaPoLi, alongside a transition to alternative fuels such as LNG, biofuels, methanol, ammonia, and hydrogen [6–9].

A comprehensive review of renewable and sustainable energy sources applicable to ships—including solar, wind, wave, nuclear, and vibration energies, as well as fuel cells and energy storage systems—has been presented by Park et al. [10], who also discuss relevant international standards, safety considerations, and future research directions for achieving net-zero emissions by 2050.

The issue of power limitation aboard vessels is multifaceted and warrants careful consideration considering the conflicting demands of safety and economic efficiency. Power limitation can be critical for accident prevention and environmental protection, yet the same restriction may cost a shipping company dearly in lost commercial performance. Striking a workable balance between these pressures is what makes the problem genuinely difficult for regulatory bodies and the industry.

Tighter environmental rules have made vessel operation considerably more demanding [9]. The resulting challenges fall into four broad categories: energy consumption, environmental compliance, technical readiness, and economics [11].

1.1. Energy Consumption Challenges

Typical vessels consume between 80 and 200 g of fuel per tonne-mile [12,13], with engines operating under partial load—a common consequence of slow steaming—incurring further efficiency penalties and elevated specific emissions [14–17]. Adapting the existing fleet to new energy efficiency requirements without compromising operational productivity therefore represents one of the central economic challenges facing the industry.

1.2. Environmental Challenges

Beyond CO₂, SO_x, NO_x, and particulate emissions from vessels degrade air quality in coastal zones and damage marine ecosystems [18,19]. Compliance with the IMO 2020 sulphur cap and subsequent EEXI and CII requirements demands costly low-sulphur fuels, scrubbers, or fuel switching. For LNG-powered vessels, methane slip—uncombusted methane released to the atmosphere, with a global warming potential approximately 25 times that of CO₂—partially offsets the fuel’s environmental benefits.

1.3. Technical Challenges

Retrofitting EPL and SHaPoLi systems requires upgraded electronic control units and dedicated sensors, while seamless mode transitions without propulsive power loss demand sophisticated control algorithms [18,19]. Alternative fuels impose further constraints: LNG and hydrogen require cryogenic storage, while ammonia and methanol demand corrosion-resistant materials and dedicated bunkering infrastructure.

1.4. Economic Challenges

Capital expenditure for fleet modernisation with dual-fuel engines and specialised storage can reach tens of millions of dollars per vessel [18,19]. Price volatility and limited port availability of LNG, hydrogen, ammonia, and methanol further complicate operational cost planning, while crew retraining and system maintenance add to the overall financial burden.

The aim of this article is a comprehensive analysis of the operational challenges facing maritime vessels in the context of decarbonization, and the development of staged

recommendations for the integration of power limitation systems and alternative fuels. To achieve this aim, the following research contributions were made:

1. A detailed analysis of the energy, environmental, technical, and economic challenges associated with the operation of the contemporary maritime fleet, along with the identification of the most promising pathways for their resolution.
2. A comparative assessment of the principal alternative fuels—LNG, biofuels, methanol, ammonia, and hydrogen—with respect to their characteristics, advantages, and challenges in the context of shipping decarbonization.
3. An analysis and description of energy consumption regulation technologies (EPL and SHaPoLi systems) within the framework of global environmental requirements, including their impact on operational efficiency and compliance with IMO regulations.

The paper first benchmarks six alternative fuels—LNG, biofuels, methanol, ammonia, hydrogen, and liquefied petroleum gas (LPG)—against one another on technical, environmental, and economic grounds. It then examines how mechanical limiters, electronic governors, CPP systems, EPL, and SHaPoLi perform against EEXI and CII requirements, before setting EPL and SHaPoLi head-to-head across thirteen criteria. The final sections address the combined effect of pairing power limitation with alternative fuels, offer practical implementation guidance for operators, and outline the research questions that remain open—among them adaptive control algorithms, hybrid propulsion, and investment appraisal tools for energy-efficient retrofits.

2. Analysis of Alternative Fuels in the Context of Shipping Decarbonization

Maritime shipping represents a significant contributor to the global environmental footprint and is subject to growing pressure to embrace greener and cleaner energy solutions [19,20]. The fleet of vessels operating on a variety of fuel types demonstrates steady growth in both the number of vessels in service and newly constructed units. In pursuing decarbonization, the maritime industry is actively exploring a broad spectrum of alternative energy carriers—from LNG to electric batteries and hydrogen technologies—which are gradually displacing or supplementing conventional fuels [8,10,20–22].

Alternative fuels are central to any credible decarbonisation roadmap for shipping, and their integration with renewable energy technologies warrants equal attention [10]. The sections below assess the most viable options currently available.

2.1. Liquefied Natural Gas

Liquefied natural gas represents a viable fuel for maritime transport, composed predominantly of methane at a concentration of no less than 85% CH₄. The energy density of LNG is approximately 55 MJ/kg, providing substantial vessel range and rendering it a competitive alternative fuel [8,9].

The use of LNG as a marine fuel demonstrates considerable environmental advantages over conventional fuels. These include a reduction in carbon dioxide emissions of 20–25% compared to heavy fuel oil, near-complete elimination of sulphur and particulate matter emissions, and a reduction in nitrogen oxide emissions of up to 85%. An additional advantage is the availability of established bunkering infrastructure in major ports worldwide, which facilitates the adoption of this fuel type [8,9].

At the same time, the use of LNG entails several technical and economic challenges. The storage and transportation of liquefied natural gas require specialised cryogenic tanks and adapted engines, resulting in high initial capital expenditure for vessel retrofit or newbuild construction. Furthermore, the methane slip problem—associated with the

release of uncombusted methane, a potent greenhouse gas—may offset a portion of the environmental benefits attributed to LNG as an alternative fuel [8,9].

At the same time, cryogenic storage requirements and high retrofit costs represent significant barriers, and methane slip may partially offset LNG's environmental benefits [8,9].

2.2. Biofuels

Biofuels are alternative fuels produced from renewable resources, including vegetable oils, animal fats, and agricultural waste. The principal types of biofuels applicable to maritime transport are hydrotreated vegetable oil (HVO) and fatty acid methyl esters (FAME). The energy density of biofuels is approximately 35–40 MJ/kg, somewhat lower than that of conventional petroleum products, yet sufficient for effective use in maritime operations [9,23,24].

A key advantage of biofuels is their status as a carbon-neutral fuel, given that CO₂ emissions produced during combustion are theoretically offset by carbon dioxide absorbed by plants during growth and photosynthesis. A notable practical advantage is the compatibility of biofuels with existing diesel engines, permitting their use without significant modification of vessel propulsion systems, or alternatively as blends with conventional diesel fuel [9,24,25].

Key limitations include constrained feedstock availability, competition with food crops for land, and the need for sustainability certification, all of which complicate supply and increase costs [24,25].

2.3. Methanol

Methanol is a monohydric alcohol with the chemical formula CH₃OH, regarded as a viable fuel for maritime transport. It can be produced by several routes: from natural gas via steam reforming, from biomass through gasification, or from carbon dioxide and hydrogen to yield electro-methanol (e-methanol). The energy density of methanol is approximately 20 MJ/kg, considerably lower than that of conventional marine fuels [9].

The principal advantages of methanol as a marine fuel include liquid storage at ambient temperature and pressure, which eliminates the need for cryogenic infrastructure, combined with near-zero sulphur and particulate emissions. When produced from renewable sources, e-methanol can achieve substantial GHG reductions [9,23,26]. However, its low energy density requires approximately twice the tank volume of conventional fuel, engines require significant modification, and methanol's toxicity demands dedicated safety protocols for storage and bunkering [9,23,26].

2.4. Ammonia (NH₃)

Ammonia is a carbon-free compound of nitrogen and hydrogen with the chemical formula NH₃, regarded as one of the most viable fuels for the decarbonization of maritime transport. Depending on the production method, a distinction is drawn between “green” ammonia—produced from renewable hydrogen obtained by water electrolysis using renewable energy sources—and “blue” ammonia, manufactured from natural gas with the application of carbon capture and storage technologies. The energy density of ammonia is approximately 18.6 MJ/kg [9,27,28].

Ammonia produces no carbon dioxide upon combustion and benefits from existing industrial production and distribution infrastructure, with moderate-pressure liquid storage conferring logistical advantages [9,27,28]. However, its high toxicity and corrosivity demand specialised materials and safety systems, engine adaptation for ammonia combustion remains a key technical challenge, and NO_x/N₂O formation during combustion requires effective exhaust treatment [9,27,28].

2.5. Hydrogen (H_2)

Hydrogen is the lightest element in the periodic table and is regarded as one of the most promising fuels for the full decarbonization of maritime transport. Depending on the production method, a distinction is drawn between “green” hydrogen—obtained by water electrolysis using electricity generated from renewable sources—and “blue” or “grey” hydrogen, produced from fossil fuels. Hydrogen possesses the highest gravimetric energy density of all fuels, at approximately 120 MJ/kg, which is approximately three times greater than that of conventional hydrocarbon fuels [9,29,30].

The principal advantage of hydrogen is its absolute environmental cleanliness in use: the combustion of hydrogen or its utilisation in fuel cells produces exclusively water vapour, yielding zero emissions of carbon dioxide and other pollutants. On this basis, hydrogen is widely considered the most environmentally aligned option for meeting the IMO’s long-term decarbonization objectives.

Hydrogen’s extremely low volumetric energy density demands cryogenic storage at $-253\text{ }^\circ\text{C}$ or pressurised vessels at up to 700 bar, both of which reduce payload capacity significantly. High green hydrogen production costs and the near-complete absence of port bunkering infrastructure require large-scale investment before maritime adoption can scale [9,29,30].

2.6. Liquefied Petroleum Gas (LPG)

Liquefied petroleum gas is a mixture of light hydrocarbons composed predominantly of propane (C_3H_8) and butane (C_4H_{10}) in varying proportions, depending on the source of extraction and producer specifications. LPG is obtained as a by-product of crude oil refining at petroleum refineries or as associated gas during natural gas production. The energy density of liquefied petroleum gas is approximately 46–50 MJ/kg, rendering it a competitive alternative to conventional marine fuels [9,31,32].

The principal advantages of LPG as a marine fuel are its relatively favorable environmental characteristics and technical accessibility. The use of liquefied petroleum gas yields a reduction in carbon dioxide emissions of 15–20% compared to heavy fuel oil, near-complete elimination of sulphur and particulate matter emissions, and a substantial reduction in nitrogen oxide emissions. LPG is stored in liquid phase at relatively moderate pressure (5–15 bar) and ambient temperature, simplifying storage systems compared to cryogenic fuels. A further advantage is the existence of a well-developed global infrastructure for the production, transportation, and storage of LPG, established to serve the needs of the chemical industry and domestic use [9,31,32].

Drawbacks include the need for pressurised storage, engine modifications, and enhanced safety systems due to flammability risk. As a fossil fuel, LPG offers only partial decarbonisation, which may limit its long-term role under increasingly stringent environmental requirements [9,31,32].

The analysis of alternative fuels for maritime transport demonstrates the diversity of available technological solutions, each characterized by specific advantages and limitations. To systematize and compare the key characteristics of the fuels examined, a summary table has been compiled, enabling a comprehensive assessment of their suitability for practical implementation in the maritime industry (Table 1).

The comparative analysis indicates the absence of a universal alternative fuel capable of fully satisfying all requirements of the maritime industry at the current stage of technological development. Each fuel type presents a characteristic trade-off between environmental benefits, technical complexity of implementation, and economic viability.

Table 1. Comparative characteristics of alternative fuels for maritime transport.

Fuel Type	Energy Density (MJ/kg)	CO ₂ Reduction (%)	NO _x Reduction (%)	Storage Type	Capital Expenditure	Infrastructure Availability	Impact on Payload	Vessel Adaptation Complexity	Key Advantages	Challenges
Liquefied Natural Gas (LNG)	~55	0–20% (subject to methane slip)	Up 85%	Cryogenic	High	Well-developed	Moderate	High	Reduced sulphur and particulate emissions; established infrastructure	Methane slip; high capital costs
Biofuels (HVO, FAME)	35–40	Carbon-neutral (theoretical)	Composition-dependent	Liquid	Low	Limited	Low	Low	Compatibility with existing engines; renewable feedstocks	Limited feedstock; competition with food supply
Methanol (CH ₃ OH)	~20	0–90% (source-dependent)	Significant reduction	Liquid at ambient temperature	Moderate	Limited	High	Moderate	Cryogen-free storage; minimal sulphur emissions	Low energy density; toxicity
Ammonia (NH ₃)	~18.6	0–100% (source-dependent)	NO _x and N ₂ O formation	Liquid/compressed	High	Limited	High	High	Carbon-free fuel; existing industrial infrastructure	Highly toxic; corrosive
Hydrogen (H ₂)	~120	100% (zero emissions)	Zero	Gaseous/cryogenic	Very high	Very limited	Very high	Very high	Absolute cleanliness; highest energy density	Low volumetric density; complex storage
Liquefied Petroleum Gas (LPG)	46–50 (composition-dependent)	10–20% (vs. conventional HFO)	Approx. 50–70%	Pressurised/low-temperature liquid	Moderate	Good (growing)	Low	Moderate	Relative accessibility; higher energy density than LNG	Specialised storage required; CO and NO _x emissions

LNG and LPG represent the most technologically mature solutions with relatively well-developed infrastructure yet deliver only moderate reductions in greenhouse gas emissions. Biofuels offer the greatest compatibility with existing systems but are subject to fundamental scalability constraints. Methanol occupies an intermediate position, offering a balance between technical complexity and environmental benefits, particularly when produced from renewable sources.

Ammonia and hydrogen offer the deepest emissions cuts but demand the most fundamental changes to shipbuilding and port infrastructure. Hydrogen's storage requirements—cryogenic tanks at $-253\text{ }^{\circ}\text{C}$ or pressure vessels at 700 bar—remain the principal barrier to its near-term adoption.

Taken together, these findings point to the need for an integrated approach in which alternative fuel adoption is pursued alongside systematic improvements in onboard energy management. Whichever fuel is adopted, onboard energy management remains the decisive factor in realising its full environmental and economic potential, which is why power regulation technologies—capable of ensuring the optimal utilisation of alternative fuels and compliance with international environmental standards—warrant close examination.

3. Analysis of Energy Consumption Regulation Technologies in Maritime Vessels: EPL and SHaPoLi Systems in the Context of Global Environmental Requirements

3.1. Energy Efficiency Indicators of Maritime Vessels

Shipping is estimated to account for approximately 2–3% of global anthropogenic CO₂ emissions [33], confirming its significant contribution to climate change. To mitigate this adverse impact, the IMO has introduced a series of regulatory measures aimed at improving vessel energy efficiency and reducing greenhouse gas emissions. These include the SEEMP for the existing fleet and the EEDI for newbuild vessels [30], as well as the recently introduced EEXI and the CII.

In studies [5,34], a methodology is proposed for calculating the Energy Efficiency Design Index (EEDI) for new vessels. These studies show that the EEDI for new vessels depends on the efficiency of technologies, the transport work performed, as well as emissions from the main engine, auxiliary engines, and the shaft generator/motor system. In turn, emissions from the main engine, auxiliary engines, and the shaft generator/motor are a function of the conversion factor between fuel consumption and CO₂ emissions, the values of which for different fuel types are presented in Figure 1 [34].

The Energy Efficiency Existing Ship Index (EEXI) defines the minimum energy efficiency level for existing vessels. The EEXI value is calculated using a reference line based on the average CO₂ emissions, expressed in tonnes of CO₂ per tonne, for ships of the same type and size. The required EEXI value is determined based on the reduction target established by the International Maritime Organization (IMO). The EEXI regulation applies to all existing vessels, regardless of their flag, age, or type, and requires compliance with the EEXI value by a specified date, typically linked to the ship's survey for license renewal. The regulation aims to promote a reduction in emissions in the maritime sector and to encourage the adoption of energy-efficient technologies and operational practices. The methodology for calculating the EEXI is presented in [4,7].

From the analysis of the EEDI and EEXI calculation methodologies, it follows that the reduction level of these indicators is directly related to a decrease in the power consumed by the vessel. The required level of EEXI reduction is defined by the reduction factor (Y), which depends on the type and size of the vessel, as well as on the Carbon Intensity Indicator (CII) (Table 2) [16].

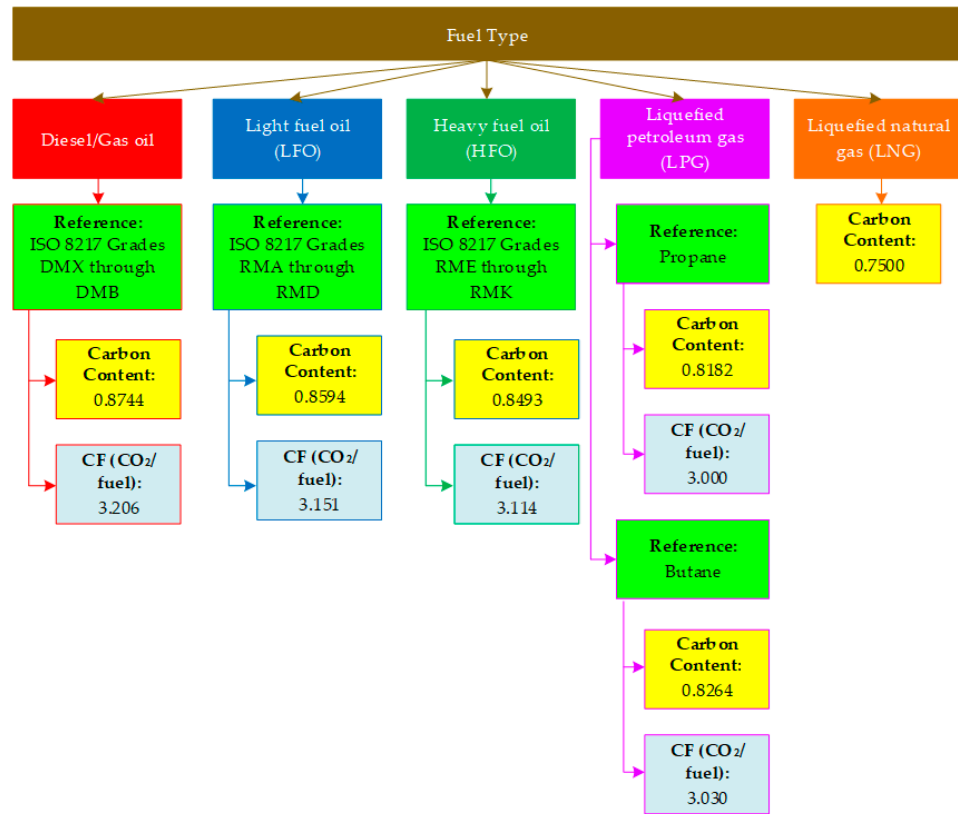


Figure 1. Conversion factors between fuel consumption and CO₂ emissions (DM—distillate marine fuels, RM—residual marine fuels. Additional letters (A, D, E, K, etc.) define the fuel category in terms of viscosity range, quality, and required fuel treatment. Inspired by the data reported in [35].

Table 2. EEXI reduction factor by ship type and capacity in combination with the CII [16].

Ship Type	Size (DWT and GT for Cruise Passenger Ship) †	Reduction Factor (Y)
Bulk carrier	10,000–19,999	0–20% *
	20,000+	20%
Gas carrier	2000–9999	0–20% *
	10,000–14,999	20%
	15,000+	30%
Tanker	4000–19,999	0–20% *
	20,000+	20%
Container ship	10,000–14,999	15–30% *
	15,000–39,999	30%
	40,000–79,999	35%
	80,000–119,999	40%
	120,000–199,999	45%
General cargo ship	200,000+	50%
	3000–14,999	0–30% *
	15,000+	15%

Table 2. Cont.

Ship Type	Size (DWT and GT for Cruise Passenger Ship) †	Reduction Factor (Y)
Refrigerated cargo carrier	3000–4999	0–15% *
	5000+	15%
Combination carrier	4000–19,999	0–20% *
	20,000+	20%
LNG carrier	10,000+	30%
Ro-ro vehicle cargo ship	10,000+	15%
Ro-ro pure cargo ship	1000–1999	0–20% *
	2000+	20%
Ro-ro passenger ship	400–999	0–20% *
	1000+	20%
Cruise passenger ship	25,000–74,999 GT	0–30% *
	75,000+ GT	30%

Note: † DWT = deadweight tonnage, GT = gross tonnage; * Reduction rate is linearly interpolated between ship sizes, with the lower target applying to the smallest ships.

The economic implications of implementing the Energy Efficiency Existing Ship Index (EEXI) in the context of global maritime decarbonization are examined in [20], where the author analyses the IMO's ambitious targets for greenhouse gas emissions reductions: 40% by 2030 and 70% by 2050 relative to the 2008 baseline.

3.2. Analysis of the Vessel Propulsion System Configuration and Justification for the Application of Power Limiters

In accordance with the conceptual frameworks for the design of maritime vessel power supply systems presented in [14,35,36], a generalised simplified power supply scheme for a maritime vessel may be represented as shown in Figure 2.

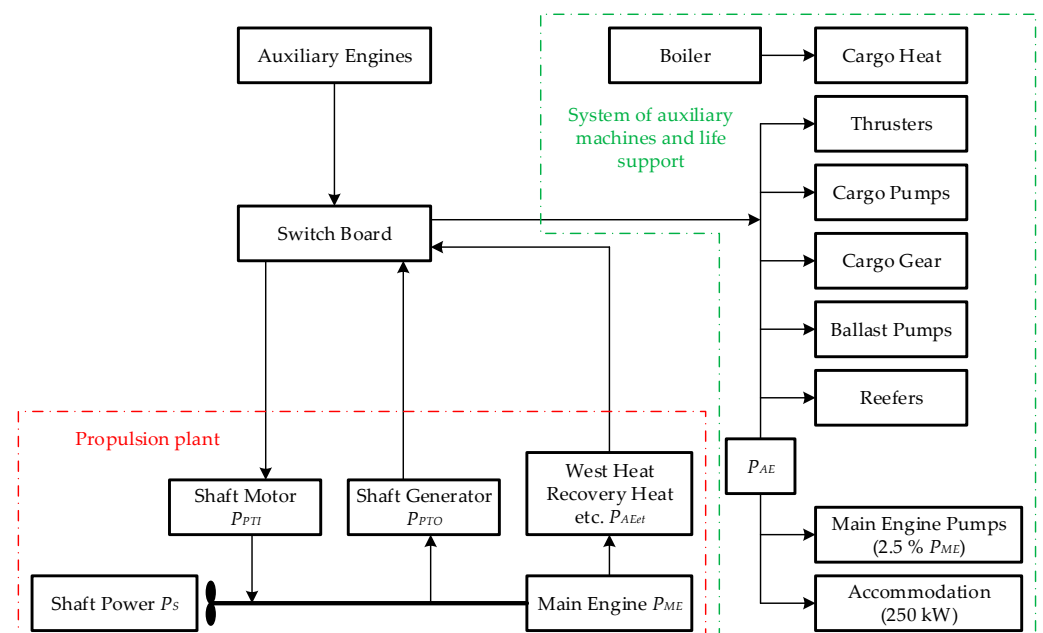


Figure 2. Generalised simplified power supply scheme of a maritime vessel.

The analysis of data presented in [6] indicates that the propulsion plant is the largest consumer of electrical energy aboard a vessel; its functional diagram is depicted in Figure 3 [37]. The functional diagram of the maritime vessel propulsion plant (Figure 3) comprises two independent shafts. Each shaft is fitted with an electric motor (Engine) which drives a propeller through a reduction gearbox (Gear). The electric motor can operate in both motor and generator modes (M/G). Two electric motors (M units in Figure 3) are engaged exclusively when the vessel enters port. The general power supply to these motors is provided by the main engine generator (G). The voltage produced by the main engine generator passes through LC-L filters to the respective converters, where it is transformed from alternating current to direct current voltage and subsequently supplied to the DC switchboard. The DC switchboard distributes voltage to the DC-to-AC converters in accordance with the operating mode. During open-sea passage, the DC switchboard supplies voltage to the converters driving the M/G motors, whose power is transmitted through the gear reducer to the propeller. The M/G motors can operate in motor mode during vessel propulsion and in generator mode during vessel deceleration. This dual-mode operation enables the application of hybrid power supply schemes aboard the vessel using energy storage systems [7,37]. Upon port entry, the DC switchboard supplies voltage to the converters driving the auxiliary thrusters (G).

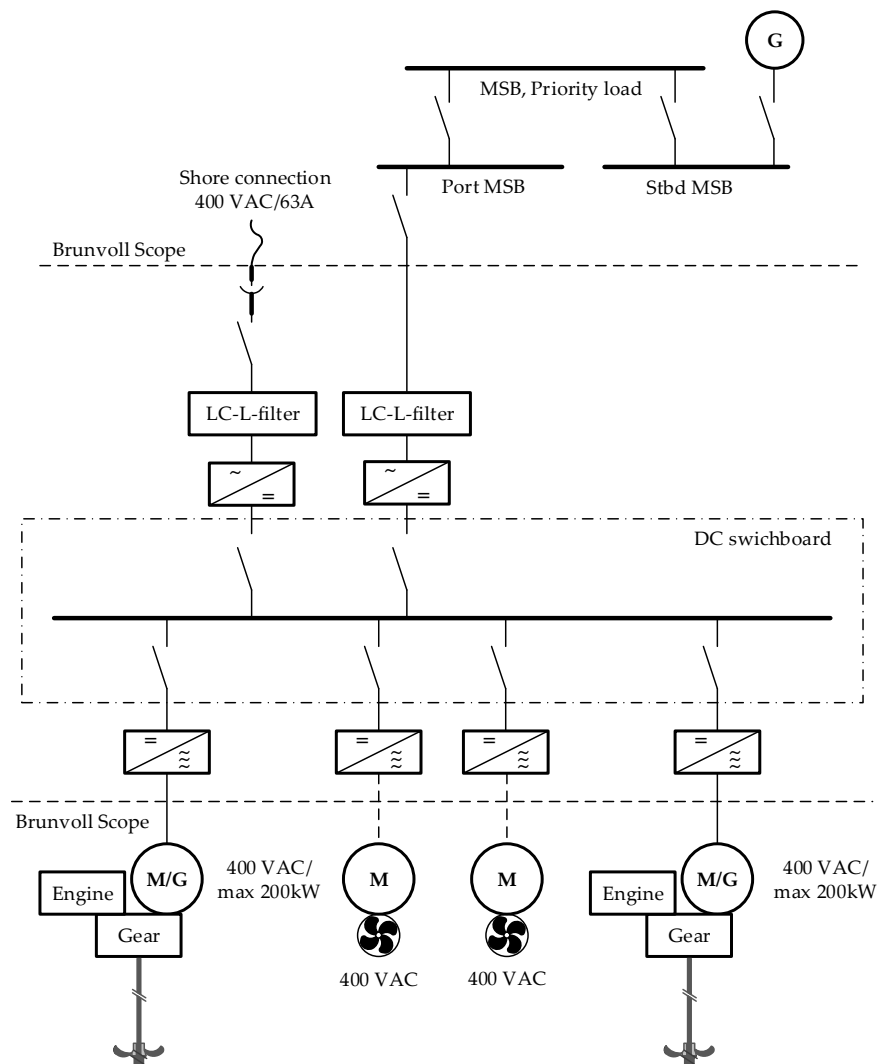


Figure 3. Functional diagram of the propulsion plant of a maritime vessel. Reproduced from [36].

Greenhouse gas emissions attributable to main engine operation are directly proportional to the active power consumed by the main engine. An analysis of the propulsion plant diagram (Figure 3) indicates that three-phase induction motors are employed as both the main engine and the propeller drive motors.

The methods for improving drive energy efficiency (reducing active power consumption) in systems with induction motors include:

- Application of hybrid power supply schemes for drives with induction motors [7,37].
- Application of reactive power compensation schemes [38–40].
- Optimisation of controller operation within the drive control system [41–43].
- Main engine power limitation (EPL) [44,45].
- Shaft power limitation (SHaPoLi) [46,47].

An analysis of the data presented in [7,37,44–47] indicates that the most effective methods for improving vessel drive energy efficiency are the application of hybrid power supply schemes, main engine power limitation, and shaft power limitation via SHaPoLi. The application of reactive power compensation schemes and the optimisation of controller operation within the drive control system may be employed as supplementary energy efficiency measures.

The application of hybrid power supply schemes requires substantially greater capital investment than main engine power limitation or shaft power limitation via SHaPoLi. Furthermore, the implementation of this method must account for the considerable mass and dimensional characteristics of energy storage systems. This approach is most effective in the design of new vessels. For vessels already in service, the most effective methods for improving drive energy efficiency are main engine power limitation and shaft power limitation via SHaPoLi. These methods, in combination with hybrid power supply schemes, reactive power compensation, and drive control optimisation, are effective for the design of new vessels.

3.3. Main EPL

The implementation of EPL systems represents one of the most effective means of achieving regulatory compliance and reducing operational costs. Engine power limitation enables the optimisation of fuel consumption, given that vessels rarely operate at maximum power under normal service conditions. The application of EPL yields substantial fuel savings, producing both environmental benefits—in the form of reduced CO₂ emissions—and economic benefits through lower fuel expenditure. Furthermore, the effectiveness of EPL can be enhanced through the concurrent application of other energy-saving measures.

Power limitation on conventional vessels equipped with internal combustion engines is directed at reducing harmful emissions and improving energy efficiency, achieved by artificially constraining engine output to a level that provides an optimal balance between performance and environmental indicators.

Power limitation aboard vessels encompasses a set of technical and regulatory requirements aimed at controlling and restricting the output power of marine engines. Its primary purpose is to satisfy environmental requirements by reducing emissions of nitrogen oxides, sulphur oxides, carbon dioxide, and other atmospheric pollutants. In addition, it facilitates fuel savings through the optimisation of fuel consumption during vessel operation [48,49].

The EPL (engine power limitation) system is a technological solution designed for the physical or software-based regulation of the maximum output of a maritime vessel's main propulsion plant. This technology is regarded as one of the most effective and economically viable means of ensuring that the existing fleet complies with the new EEXI energy efficiency requirements established by the IMO.

Figure 3 shows how the system's core components interact and how control signals propagate through it. The operating principle of the EPL system is based on the imposition of software or hardware constraints on key engine operating parameters—particularly the fuel injection system—thereby guaranteeing that the established maximum power level is not exceeded [50,51]. The detailed structure of the system and the interrelationships between its elements are presented in Figure 4.

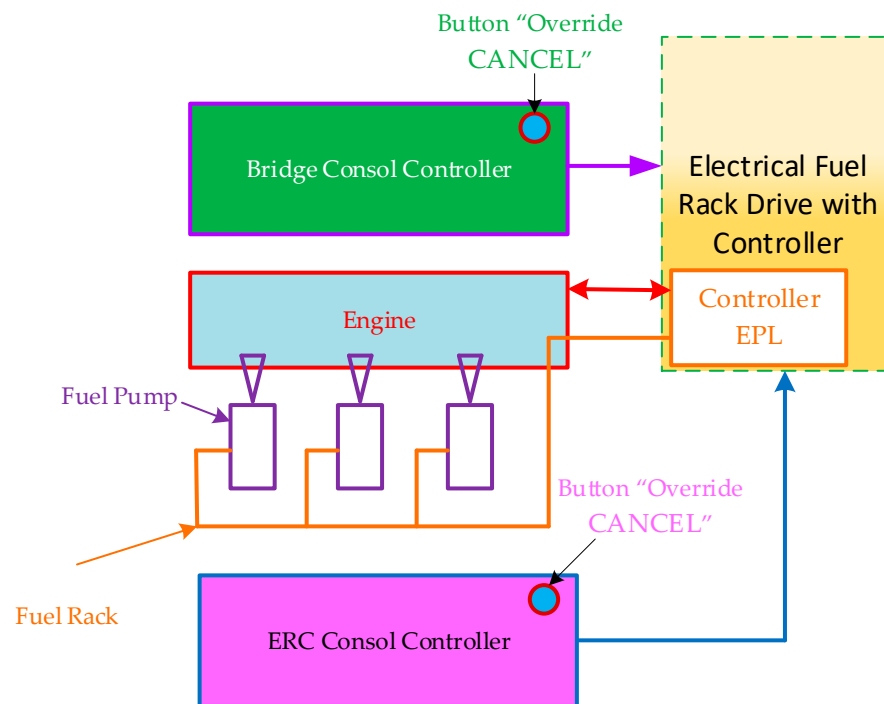


Figure 4. Functional diagram of the EPL engine power limitation system.

The EPL system rests on continuous monitoring of two critical parameters: cylinder combustion pressure and exhaust gas temperature. The central processing element is the EPL unit, which processes input signals and generates control commands for the fuel injection regulator.

In accordance with the diagram in Figure 4, the measurement subsystem comprises cylinder combustion pressure sensors, which continuously monitor peak pressure in the combustion chamber, and exhaust gas temperature sensors, which enable assessment of the thermal load on the engine. Signals from these sensors are transmitted to the EPL unit, where they are compared against the established threshold values corresponding to the limited engine power. Upon reaching critical parameters, the system generates a control action on the fuel rack via the regulator, restricting the maximum cyclic fuel delivery and, consequently, the indicated engine output.

The system architecture detailed in Figure 4 provides for the integration of the EPL unit with the engine governor tuning system, ensuring coordinated control of propulsion plant operating modes. The fuel rack—the system's actuating mechanism, clearly depicted in Figure 4—applies mechanical restriction to the maximum travel of the fuel pump actuator, physically preventing the delivery of excessive fuel quantities to the cylinders. This configuration ensures that the established power threshold cannot be exceeded even in the event of manual operator intervention.

The functional diagram presented in Figure 4 demonstrates the fundamental feasibility of constructing a reliable engine power limitation system with minimal response time to changes in operating parameters. The combustion pressure feedback loop ensures

regulation accuracy and protects the engine against operation under conditions of excessive mechanical and thermal loading.

However, EPL implementation must align with IMO requirements of its architecture considering the requirements of the IMO, which regulates not only the technical aspects of power limitation but also the mandatory safety and monitoring elements. In particular, in accordance with Resolution MEPC.328(76), the EPL system must incorporate an emergency override mechanism and a logging system for all instances of full engine power utilisation. The architectural organisation of the EPL system in compliance with IMO requirements provides for the integration of additional mandatory components, ensuring safe vessel operation in emergency situations and the documentation of propulsion plant operating modes [52,53], as presented in Figure 5.

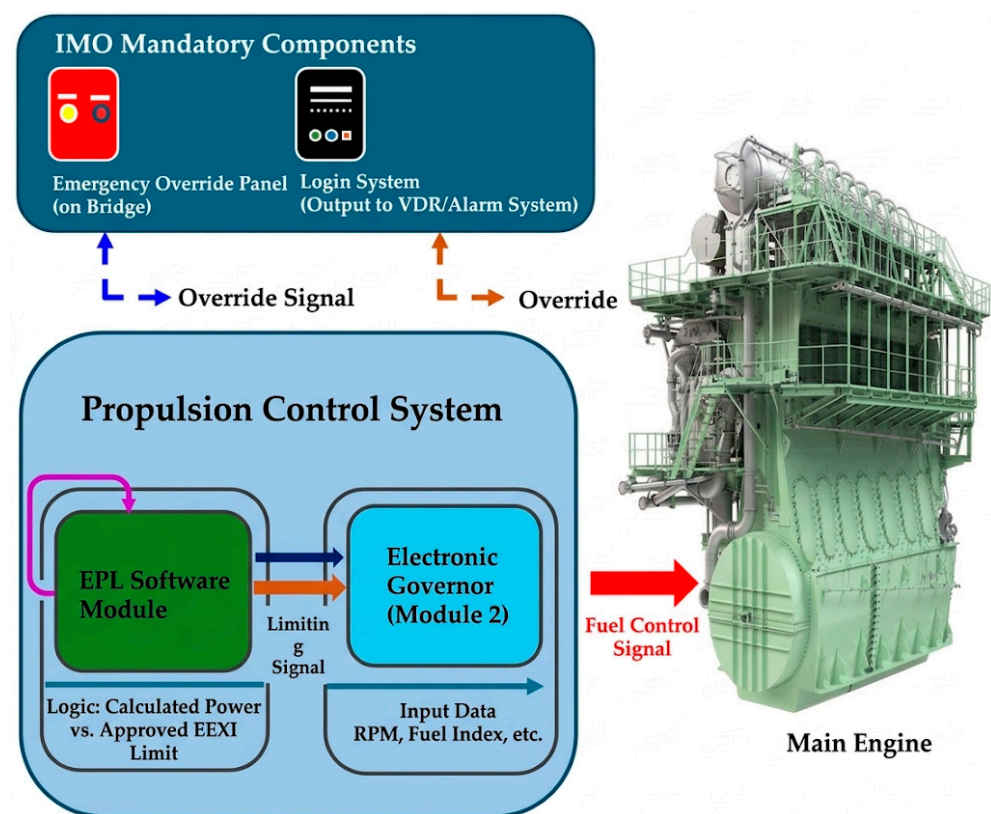


Figure 5. Architecture of the EPL engine power limitation system with mandatory IMO components.

The block diagram presented in Figure 5 reflects the systemic organisation of the EPL in accordance with IMO requirements, incorporating the mandatory safety and monitoring elements. The system architecture (Figure 5) includes two principal functional blocks: the mandatory IMO components and the propulsion management system. The EPL software module calculates logical power and compares it against approved EEXI limits.

In accordance with the diagram in Figure 5, the EPL software module is integrated with an electronic governor, which receives input data on engine speed, fuel index, and other operating parameters. When the established power limit is exceeded, the module generates a limitation signal that is transmitted to the electronic governor to correct the fuel delivery control signal to the main engine. This architecture, detailed in Figure 4, enables software-based power control without requiring physical modification of the fuel injection equipment.

A critically important element of the system, clearly depicted in Figure 5, is the emergency override panel located on the navigation bridge. This mandatory IMO component enables the vessel's command staff to temporarily deactivate the power limitation in

emergency situations via an override signal. In accordance with the requirements presented in Figure 5, any activation of the emergency override function is automatically recorded by the logging system, which captures the precise time of activation, the duration of unrestricted operation, and transmits this data to the voyage data recorder or alarm management system.

The system architecture shown in Figure 5 ensures full compliance with IMO requirements regarding transparency of power limitation use and the verifiability of data by regulatory authorities. The logging system creates an immutable record of all events associated with EPL operation, which constitutes a mandatory prerequisite for confirming vessel compliance with the EEXI during port state control inspections and periodic surveys by classification societies.

Several types of power limiters exist aboard vessels, classifiable by their operating principle: mechanical limiters, electronic limiters, and limitation via controllable pitch propellers (CPP).

3.3.1. Mechanical Limiters

These systems employ mechanical devices to physically restrict the maximum power output of the engine or propeller shaft. The design of such systems is based on automatic speed control systems (ASCS) for the main engine shaft. ASCSs comprise the main engine as the controlled object and a speed governor.

The primary function of the ASCS is to set and stabilise the speed regime of the main engine. The ASCS also performs main engine load limiting and emergency fuel cut-off functions. The central issue in the analysis of ASCS operation is the evaluation of its dynamic characteristics.

The vessel's main engine serves as the source of mechanical energy. On many vessels, internal combustion engines predominate as the source of mechanical energy. An internal combustion engine is an assembly of interacting elements comprising the engine itself—which includes the block with combustion chambers, cylinder-piston assemblies, and the crankshaft. The input variables of the engine are cyclic fuel delivery g_t , air supply G_D and load N , while the output variables are— ω_d (crankshaft angular velocity ω_n) and G_g (gas flow to the exhaust manifold). For the fuel injection system, cyclic fuel delivery g_t is the output variable, while the rack control position h is the input variable. Since g_t of the plunger fuel pumps is substantially dependent on crankshaft angular velocity ω_n the latter constitutes the second input variable of the fuel injection system [54].

The functional diagram of the main engine is presented in Figure 6. The parameters governing the main engine operating mode are: N_e —effective power; T torque; ω_d —crankshaft angular velocity; g_e —effective specific fuel consumption; η_e —effective thermal efficiency, and others.

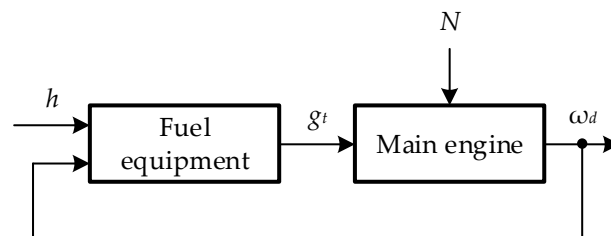


Figure 6. Block diagram of the vessel's main engine as a controlled object. Inspired by the concepts reported in [53].

For the main engine to operate in a stable regime, the conditions of static equilibrium must be satisfied. The temporal stability of the angular speed ω_d in steady-state operation is achieved when the driving torque T is equal to the resisting torque T_c generated by the

generator [54]. The load (consumer) resisting torque T_c is a function of the angular speed ω_d and the load parameters N .

Strength-related, thermal, and gas-dynamic constraints influence the parameter values that define the feasible stable operating regimes of the main engine. The presence of unstable regimes leads to either an excess or a deficit of energy within the main engine. When the driving torque increases, the angular speed ω_d also increases.

The cyclic fuel supply and the completeness of its combustion determine the torque of the main engine. The completeness of fuel combustion is a function of the amount of air supplied to the combustion chamber. Therefore, the selection of the air intake system is based on the condition of providing sufficient air to the cylinders under nominal operating conditions. To eliminate the dependence of the main engine torque on the air pressure in the intake manifold, the air supply should be chosen to ensure complete fuel combustion. The cyclic fuel supply is a function of the control input position and the angular speed of the crankshaft ω_d .

According to [54], the control element of the main engine can be influenced by a speed governor. Automatic indirect control regulators typically include a sensing element, as well as amplification and auxiliary components [54]. To ensure accurate maintenance of the desired operating regime under all load conditions, an isochronous governor with flexible feedback should be applied (Figure 7) [54].

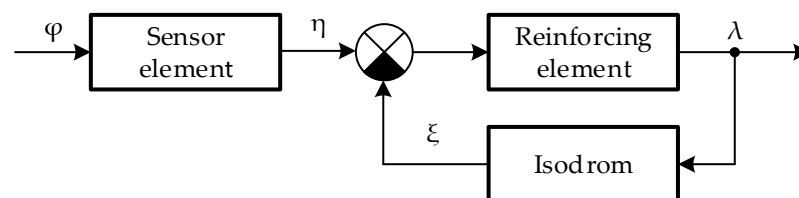


Figure 7. Block diagram of an indirect-action governor with isochronous feedback. Inspired by the concepts reported in [54].

The following hydromechanical governor types are used as speed governors:

- Governors with hydraulic power isochronous feedback [54,55].
- Governors with hydromechanical power isochronous feedback [56,57].
- Governors with hydromechanical kinematic isochronous feedback [58,59].

Governors with hydraulic and hydromechanical power isochronous feedback have a similar structural configuration. In both types, the control spool, the speed-setting spring, and the power differential piston perform the same functions. The key difference is that, in governors with hydromechanical power isochronous feedback, the plunger is equipped with two control lands: one opens the pressure ports, while the other opens the return (drain) ports.

The structure of governors with hydromechanical kinematic isochronous feedback differs from that of governors with hydraulic power isochronous feedback and hydromechanical power isochronous feedback by the presence of an additional summing unit for the isochronous feedback output signal [58,59].

Mechanical power limiters provide reliable physical restriction of the maximum fuel delivery to the engine. The principal advantage of mechanical systems is their absolute reliability, independence from electrical power supply, and the simplicity of verifying vessel compliance with EEXI requirements during classification society inspections. However, mechanical limiters are characterised by limited flexibility in power management and an inability to adapt promptly to changing operational conditions without physical intervention in the system configuration.

3.3.2. Electronic Limitation Systems

These systems employ electronic controllers to monitor and restrict engine or propeller shaft power. They enable more precise and flexible power regulation, as well as integration with other shipboard systems, such as the engine monitoring and management system. Electronic limiters can be programmed for various operating modes and can account for multiple factors, including operating conditions and engine state.

Electronic limiters utilise an electronic governor that replaces mechanical components with sensors and an actuating mechanism. The principal elements of the block diagram of an electronic power limitation system are the rotational speed sensor, the electronic control unit, the speed setpoint device, the actuating mechanism, and the fuel rack. The speed sensor is a magnetic or optical transducer that reads the actual rotational speed of the crankshaft. The electronic control unit serves as the central element of the system, receiving the signal from the speed sensor and comparing it with the setpoint signal supplied from the control station on the bridge or in the engine room. The actuating mechanism is an electric solenoid or electrohydraulic servomechanism that physically displaces the fuel rack to regulate fuel delivery to the engine.

The operating principle of the electronic system consists of the continuous comparison of actual rotational speed against the desired speed by the electronic control unit. If the actual speed exceeds the set value or approaches the established power limit, the control unit generates a corrective signal to the actuating mechanism, which displaces the fuel rack in the direction of reduced fuel delivery. Electronic power limitation is implemented as software within the electronic control unit, which simply prevents the actuating mechanism from exceeding a predefined maximum fuel rack position.

Electronic governors used on ships include the EGS 2000 [60], DEGO II [61], and DGS 8800 [62]. The EGS 2000 implements a proportional control law, while the DEGO II uses a proportional–integral–derivative (PID) control strategy. The DGS 8800 has a structure like that of the DEGO II. In addition, the DGS 8800 incorporates a signal filtering function that is automatically activated at low engine speeds. This filter improves control stability in very low-speed and low-cylinder diesel engines, which typically exhibit higher rotational irregularity.

The technical implementation of electronic power limitation systems is based on the integration of electronic controllers with mechanical actuating devices of the engine fuel system. In [63,64], the authors analysed the operation of a typical EPL electronic system configuration. In this arrangement, control signals from bridge or engine room control stations are transmitted to an electronic controller, which, via a governor, converts electrical signals into mechanical displacement of the fuel pump rack. This establishes a software-defined limit on maximum fuel delivery, directly restricting engine output power in accordance with the EEXI requirements.

The emergency override function enables the crew to temporarily deactivate the electronic limitation by pressing the corresponding button on the bridge or engine room controllers, allowing the fuel rack to move beyond the established limit to increase engine power in critical situations.

The result is a setup that preserves the crew's ability to respond to emergencies whilst keeping the vessel within its IMO-mandated power envelope under normal conditions.

3.3.3. Power Limitation via Controllable Pitch Propellers (CPP)

Electronic power limitation systems implemented through EPL controllers provide effective management of fuel delivery to the main engine; however, their functionality is confined to the regulation of engine operating parameters. An alternative approach to power limitation is the management of the propulsion system at the level of the propeller,

which permits modification of the vessel's thrust characteristics without intervention in the operating modes of the propulsion plant. Contemporary vessels may be equipped with two fundamentally distinct types of propulsion systems: fixed pitch propellers (FPP) [65,66] and controllable pitch propellers (CPP) [67,68]. Fixed pitch propellers are features by simplicity of design and reliability but offer limited flexibility in the management of thrust characteristics. CPP systems provide substantial operational advantages that are critically important for compliance with the requirements of contemporary environmental regulations, particularly the EEXI.

The principal advantage of CPP systems for the implementation of power limitation is the ability to modify the vessel's thrust characteristics without altering the rotational speed of the main engine, thereby enabling the engine to be maintained at its optimal operating point irrespective of prevailing service conditions. Unlike EPL systems, which restrict maximum engine power at the level of the fuel system, CPP systems allow the engine to operate across a wide range of rotational speeds while controlling actual thrust through variation in the propeller blade pitch. This architecture is particularly effective for vessels operating under conditions of frequent load changes, manoeuvring in confined waters, or equipped with shaft generators, where a steady engine speed is essential for stable power generation.

Power limitation systems employing controllable pitch propellers utilize electronic controllers to monitor and regulate the propeller blade pitch angle [69,70]. They enable more precise and flexible control of the power transmitted to the propeller without altering engine rotational speed. The CPP system can be programmed for various operating modes and configured to account for multiple factors, including vessel speed, service conditions, and engine state. This ensures optimal engine and propeller performance, minimizing fuel consumption and harmful emissions (Figure 8).

CONTRABLE PITCH PROPELLER (CPP) LIMITATION

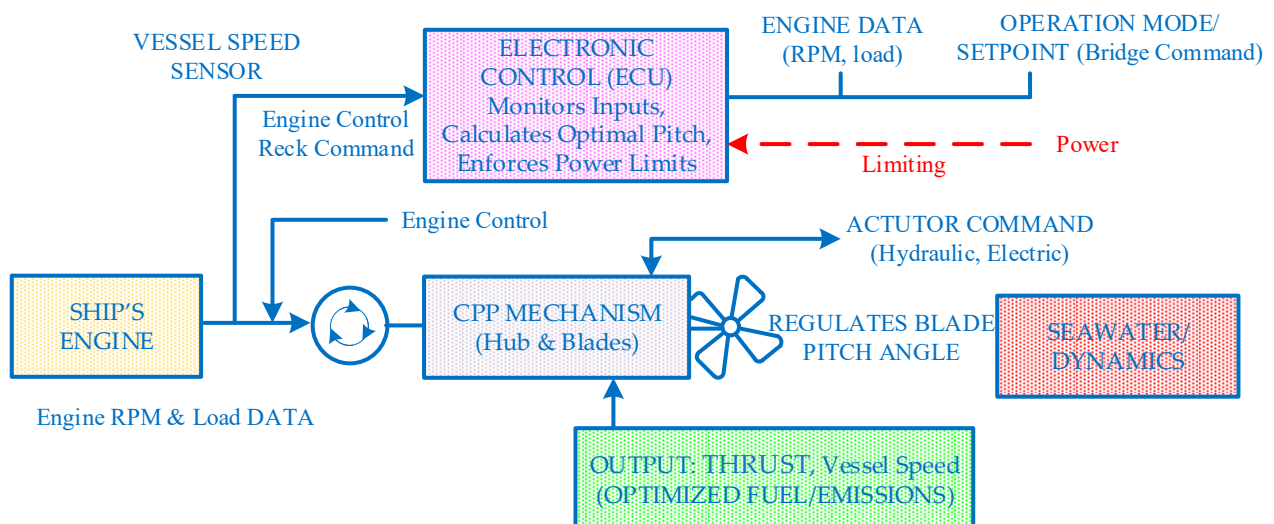


Figure 8. Functional diagram of power limitation via a controllable pitch propeller system.

The principal advantages of controllable pitch propellers include the ability to modify thrust characteristics without altering the rotational speed of the main engine, thereby ensuring optimal matching of the propulsion system to prevailing service conditions [71].

CPP systems enable vessel reversal without the need to change the direction of shaft rotation, significantly reducing maneuvering time and enhancing navigational safety in confined waters. A further advantage is the ability to precisely apportion power through

blade pitch variation, which creates ideal conditions for the integration of automatic engine load limitation systems in compliance with EEXI requirements without compromising vessel maneuverability.

The technical implementation of CPP systems is based on a complex hydromechanical architecture comprising several interrelated functional subsystems [72]. The hydraulic pitch control system supplies working fluid at regulated pressure to the actuating mechanisms of the propeller hub. The central element of the system is the oil distributor, mounted on the rotating shafting, which transmits hydraulic energy from the stationary part of the system to the rotating propeller hub. The source of hydraulic pressure consists of two electrically driven variable displacement axial piston pumps, which enable precise regulation of blade displacement speed and force in the ahead and astern directions. Pump redundancy ensures system operability even in the event of failure of one unit, in accordance with the safety requirements applicable to marine propulsion plants.

The integration of mechanical and hydraulic CPP components with electronic control systems establishes the technological foundation for the implementation of automated main engine power limitation algorithms. This integration enables real-time propeller pitch adaptation to specified load limits, keeping the vessel EEXI-compliant without compromising propulsion performance.

The practical realisation of power limitation on vessels equipped with controllable pitch propellers is achieved through integration with electronic remote-control systems. An example of such integration is the BERG Propulsion ERC 3000 system (Figure 9) [73], which provides comprehensive electronic control of propeller pitch and main engine speed with automatic load management and multi-level overload protection.

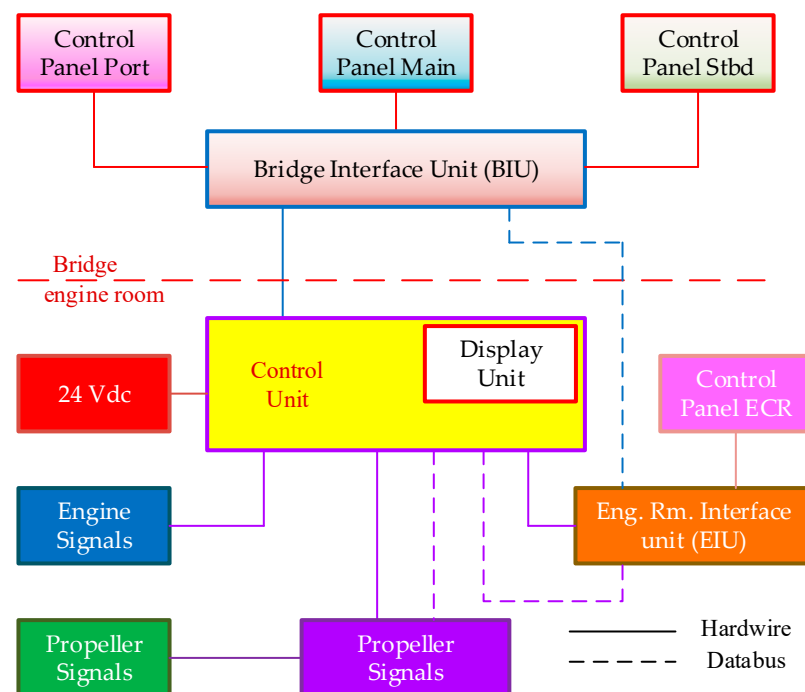


Figure 9. Block diagram of the BERG Propulsion ERC 3000 electronic remote control system architecture for controllable pitch propeller power limitation.

The block diagram of the ERC 3000 remote control system, presented in Figure 9, illustrates the interrelationships between the Central Unit, Local Units, Bridge Interface Units, and Engine Room Interface Units. The Central Unit incorporates a PLC (programmable logic controller) and employs data bus communication for the transmission of data, includ-

ing engine and propeller input signals. The Local Unit, located in the engine room, contains the pitch controllers and is powered by a 24 VDC backup power supply.

The architecture of contemporary CPP systems for power limitation comprises three principal functional blocks:

The 'Load Control System' functions as an automated regulator that maintains a constant load on the main engine irrespective of external operational factors such as sea state or varying hydrodynamic hull resistance. The system continuously compares actual load parameters against the permissible limits set by the operator. The permissible load regulation range extends from 60% to 100% of rated engine power, providing flexibility in managing vessel energy efficiency in accordance with EEXI requirements. Upon detection of a limit exceedance, the system automatically reduces propeller pitch to prevent overloading of the propulsion plant. Limit parameter settings are configured via a high-precision multi-turn potentiometer integrated into the engine room control panel, and deviations from established limits are indicated via a dedicated indicator lamp.

The 'Speed Controller' provides independent linear adjustment of the desired main engine rotational speed, separately from the propeller pitch control system. Of particular significance is the Constant RPM mode, which is critically important for vessels equipped with shaft generators for power generation. In this mode, engine speed is fixed at a pre-determined level, while thrust management is performed exclusively through propeller pitch variation in accordance with a linear algorithm independent of the standard combinator curve. This configuration enables the optimization of power generation whilst simultaneously controlling the vessel's propulsive characteristics.

The 'Safety Limiters' constitutes a multi-level propulsion plant protection system providing automatic protection of the main engine against critical operating conditions and emergency situations. This subsystem is an integral component of CPP power limitation systems and performs two key functions: prevention of equipment damage due to overloading, and automatic adaptation of operating parameters in response to signals from other shipboard safety systems.

The 'Overload Protection' system is activated upon the attainment of critical fuel delivery parameters to the main engine. The technical implementation of this protection is based on a high sensitivity microswitch installed directly on the engine fuel rack. This sensor continuously monitors the position of the fuel delivery rack and generates an alarm signal upon reaching the limit position corresponding to 100% maximum fuel delivery. Upon sensor actuation, the system automatically initiates a protective action sequence: a warning signal is first generated for the crew via a dedicated indicator lamp on the control panel, after which, if the situation is not corrected by the operator within the established time delay, the system automatically reduces propeller pitch to decrease engine load. This multi-stage protection logic provides the opportunity for manual operator intervention prior to activation of the automatic limitations, whilst maintaining guaranteed equipment protection against critical overloading.

The 'Auto-Load Reduction (ALR)' system, also referred to as the Slow Down function, constitutes an intelligent adaptive power management algorithm that responds to signals from various shipboard monitoring systems. Unlike the overload protection system, which responds exclusively to fuel delivery parameters, the ALR system is integrated with a wide range of vessel sensors and safety systems, including exhaust gas temperature monitoring systems, charge air pressure monitoring systems, cooling water temperature control systems, oil leak detection systems, and other critically important propulsion plant operating parameters.

Upon receipt of an alarm signal from any of the connected safety systems—for example, upon detection of excessive exhaust gas temperature, which may indicate inefficient

fuel combustion or cooling system problems, the ALR system automatically reduces the permissible maximum engine load to a pre-established safe level. The typical value of this limitation is 60% of rated engine power, which corresponds to an operating mode with an adequate safety margin for most emergency situations. Load reduction is implemented through software limitation of the maximum permissible propeller pitch, ensuring a smooth and controlled power reduction without abrupt fluctuations that could create additional risks to vessel safety or passenger comfort.

A key feature of the ALR system is its graduated response to different types of alarm signals. Depending on the nature and criticality of the detected anomaly, the system may apply different levels of power limitation—ranging from a minor reduction to 80–85% for warning signals to a significant restriction to 50–60% for critical emergency situations. Following rectification of the cause of ALR system actuation and operator confirmation of normalized engine operating parameters, the system may be manually deactivated through a dedicated reset procedure documented in the vessel's operating instructions.

The interrelationship between engine speed and propeller pitch during maneuvering is governed by a software-defined combinator curve, which reflects the established power limitations (Figure 10) [73].

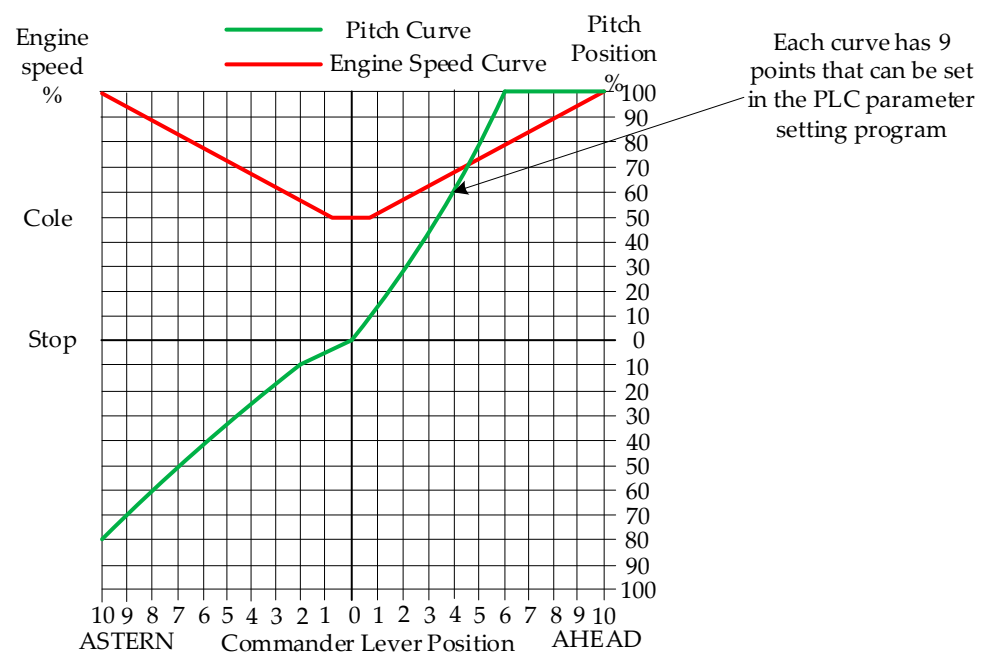


Figure 10. Combinator curve of the CPP system illustrating the interrelationship between engine speed and propeller pitch under various power limitation operating modes.

This curve constitutes a graphical representation of the established power limitations and the optimal ratios between engine speed and propeller pitch for various service regimes. The parameters of the combinator curve can be adapted to the specific requirements of a particular vessel, propulsion plant type, and the necessity of EEXI compliance. During normal operation, the system automatically follows the trajectory defined by the combinator curve, ensuring an optimal balance between performance and energy efficiency. Under operating modes with activated power limiters or upon actuation of the protection systems, the working point on the combinator curve automatically shifts towards the reduced load zone, which is visually indicated on the corresponding graphical displays of the control panel.

In constant RPM mode, engine speed is fixed at a constant value, and vessel thrust management is performed exclusively through propeller pitch variation in accordance with a linear algorithm independent of the standard combinator curve.

EPL's main selling point is cost. Capital outlay is modest compared to alternative fuel conversion, and integration with existing systems is relatively straightforward.

The speed of implementation and ease of integration with existing shipboard systems allow regulatory compliance to be achieved within a short timeframe. Reduced fuel consumption leads to lower operational costs, while engine operation at reduced power levels contributes to decreased equipment wear and improved operational reliability.

At the same time, the EPL system has certain limitations and drawbacks that must be considered during implementation. A reduction in the vessel's maximum speed may adversely affect voyage schedules and the competitiveness of shipping companies in the market. The potential increase in voyage duration may give rise to additional crew maintenance and charter costs, partially offsetting the economic benefits derived from reduced fuel consumption. EPL is best understood as a bridging measure—useful now, but insufficient on its own for the deep decarbonization the sector ultimately needs.

3.4. SHaPoLi Systems (Shaft Power Limitation)

The SHaPoLi shaft power limitation system represents a technological solution that controls and regulates the power transmitted directly to the vessel's propeller shaft and propulsor [74]. Unlike EPL systems, which limit power at the engine level, SHaPoLi acts directly on the power reaching the propeller rather than the engine output. The result is a closer match to actual propulsion loads on the propulsion complex and ensures an optimal ratio between energy expenditure and vessel propulsion efficiency.

The SHaPoLi system works by continuously measuring shaft torque and rotational speed, then computing actual propulsive power in real time. The operating principle of the SHaPoLi system is based on the continuous measurement of torque and rotational speed of the propeller shaft, followed by calculation of the actual power transmitted to the propulsor. The general system structure and the interrelationships between its elements are addressed below.

The functional diagram examined in Figure 11 reflects the theoretical organisation of the SHaPoLi system at the level of algorithmic component interaction. However, a full understanding of the practical implementation of the system requires consideration of its physical realisation aboard the vessel, including the specific placement of measurement sensors on the propeller shaft and their integration with the hull structure. Particular attention in the design of the SHaPoLi system is devoted to the installation points of strain gauge sensors, which must ensure maximum torque measurement accuracy whilst exerting minimal influence on the structural integrity of the shafting and its vibrational characteristics.

Figure 11 illustrates the practical implementation of the shaft power limitation system employing SHaPoLi technology under real shipboard conditions. As shown in Figure 11, the key element of the system is the shaft power sensors installed directly on the propeller shaft between the main engine and the propeller. The configuration presented in Figure 11 reflects a typical system layout for vessels with a single-shaft propulsion plant, where strain gauge sensors are positioned in a readily accessible section of the shafting to facilitate maintenance operations. The primary objective of SHaPoLi implementation is the optimisation of maritime vessel energy consumption and the reduction of carbon dioxide emissions through more precise control over the actual power expended on propulsion. Data collected by the system are automatically documented to confirm compliance with EEXI requirements and are made available to regulatory authorities as required. In cases of excess power exceedance—for example, under adverse weather conditions, rescue operations, or maintenance—the module records the precise time and cause of the deviation. The system adjusts propulsive power in response to prevailing operational conditions, including hydrometeorological factors, vessel loading, and speed requirements. In accor-

dance with IMO requirements, the SHaPoLi system is an effective instrument for achieving compliance with both the EEXI and for improving Carbon Intensity Indicator (CII) ratings. Since the CII evaluates vessel energy efficiency based on actual CO₂ emissions per tonne-mile, precise propulsive power management is what determines CII performance in practice. The implementation of SHaPoLi systems is characterised by several technological advantages [75]. More precise control over actual propulsive power enables higher energy efficiency to be achieved compared to systems that limit engine power alone. Parameters can be tuned to suit different operational scenarios and adjusted as weather conditions change, which pays off in day-to-day fuel bills. An additional advantage is the reduction in mechanical loading on transmission components and the propeller, contributing to an extension of their service life. At the same time, the SHaPoLi system has certain technical and operational limitations. The complexity of integration and installation significantly exceeds the requirements of EPL software solutions, resulting in higher capital expenditure for implementation. System operation necessitates the installation of additional high-precision torque and shaft rotational speed sensors, as well as a sophisticated monitoring and data processing system. The main operational risk is reduced manoeuvrability or top speed in an emergency, which makes a reliable emergency override non-negotiable from a safety standpoint [75].

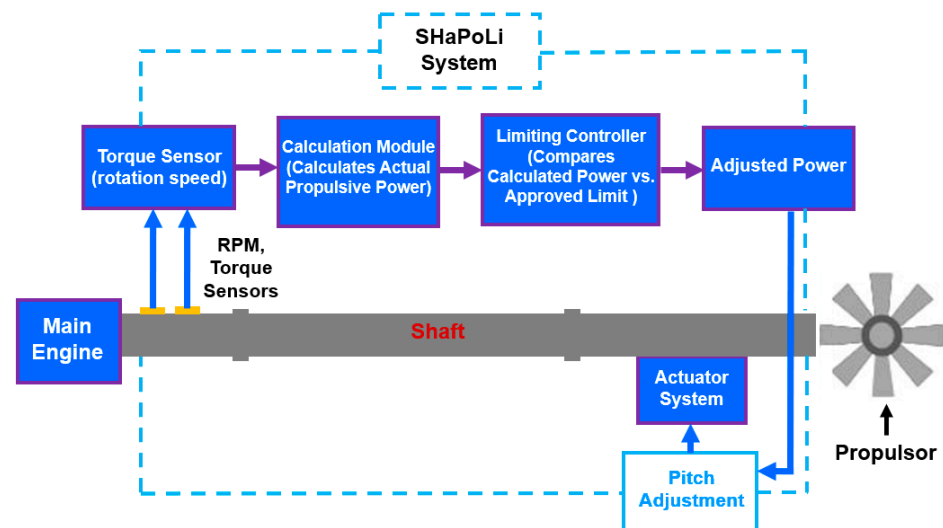


Figure 11. Functional diagram of SHaPoLi system installation on the shafting.

To evaluate the effectiveness of EPL and SHaPoLi system implementation, it is necessary to consider the specific energy intensity reduction requirements for different vessel types established by IMO regulations. The EEXI and the CII prescribe differentiated targets depending on vessel type and size, necessitating an individualised approach to the selection of an optimal power limitation strategy [76]. An analysis of the regulatory requirements demonstrates that the most stringent restrictions are imposed on large-capacity container ships, which are traditionally demonstrated high operational speeds and, correspondingly, elevated energy consumption. Bulk carriers and tankers, despite their considerable size, are subject to somewhat less stringent energy intensity reduction requirements, attributable to their typical operating profiles. Table 3 systematises the principal energy efficiency reduction parameters that different vessel categories must achieve in order to comply with international environmental standards.

Table 3. Energy intensity reduction requirements for different vessel types in accordance with IMO regulations.

Vessel Type and Capacity	EEXI Reduction Factor (%)	CII Operational Carbon Intensity Reduction (%)
Bulk carriers > 25,000 DWT	15–20	2–5 (annually)
Tankers > 50,000 DWT	18–22	2–5 (annually)
Container ships > 8000 TEU	20–25	2–5 (annually)
Cruise vessels	10–15	2–5 (annually)
Ro-ro vessels	12–18	2–5 (annually)

Note: Actual values may vary depending on the specific characteristics of the vessel and its operational profile.

The analysis of energy consumption regulation technologies in maritime vessels demonstrates that EPL and SHaPoLi systems are key instruments for achieving compliance with contemporary international environmental requirements. The implementation of these technologies enables shipping companies to ensure EEXI compliance and improve CII ratings without fundamental restructuring of the existing fleet.

The EPL system offers relative ease of implementation and low capital expenditure, making it an attractive solution for large-scale deployment on existing vessels. At the same time, the SHaPoLi system provides more precise control over actual propulsive power, enabling higher energy efficiency to be achieved, particularly under variable operational conditions [76].

The analysis of differentiated EEXI requirements for different vessel types confirms the necessity of an individualized approach to the selection of an optimal power limitation strategy. Container ships require the most significant reduction in energy intensity (20–25%), which justifies the adoption of combined solutions or the more sophisticated SHaPoLi systems [76].

Both systems carry trade-offs—chiefly the risk of speed reduction and the obligation to fit a reliable override. Neither can be bolted on without thinking through the vessel’s specific operational profile first, considering the specific operational characteristics of each individual vessel.

The findings of the study indicate that EPL and SHaPoLi systems represent an effective interim solution on the pathway to full decarbonization of maritime transport; however, their application must be considered within the broader context of a transition strategy towards alternative fuels and the uptake of emerging energy-saving technologies.

4. Discussion

Power limitation in maritime shipping sits at the intersection of three competing pressures: environmental compliance, operational economics, and navigational safety. With the sector responsible for roughly 2–3% of global CO₂ emissions, the stakes of getting this balance wrong are considerable.

Engine power limitation (EPL) and shaft power limitation (SHaPoLi) represent promising instruments for achieving compliance with the Energy Efficiency Existing Ship Index (EEXI). A comparative analysis of these systems (Table 4) demonstrates significant differences in their technical characteristics, operational features, and economic efficiency. The effectiveness of these measures is confirmed by the substantial potential for fuel cost reduction, given that vessels rarely operate at maximum power under normal service conditions. As shown in Table 4, the SHaPoLi system delivers greater reductions in fuel consumption (up to 12–18%) and CO₂ emissions (12–20%) compared to EPL (10–15% and 10–15% respectively) yet comes with higher implementation costs and more complex man-

agement. Particular attention is warranted by the differentiated approach to determining the EEXI reduction factor (Y), which ranges from 0 to 50% depending on vessel type and size, demonstrating the flexibility of the regulatory requirements.

Table 4. Comparative analysis of EPL and SHaPoLi power limitation systems.

No.	Criterion	EPL (Engine Power Limitation)	SHaPoLi (Shaft Power Limitation)
1	Operating principle	Limitation of maximum engine power [6,77,78]	Limitation of maximum power at the propeller shaft [6,79]
2	Impact on vessel speed	May reduce speed; limits peak power [6,77,78,80]	Minimal impact on speed; dynamic power regulation [6,79]
4	EEXI compliance (IMO 2023)	Direct engine power limitation ensures compliance [6,77–82]	Propeller shaft limitation to achieve the same objectives [6,79,81]
5	Operational flexibility	Lower flexibility; may require contract renegotiation [77,79,82]	Higher flexibility; temporary override capability [6,79,82]
6	Implementation costs	May be a lower-cost mechanical or electronic solution [6,77,78,80,82]	Often requires propulsion management system upgrade; higher cost [6,79,82]
7	Fuel consumption reduction	Up to 10–15% with power limitation applied [6,77,78,80,82–84]	Up to 12–18% through propeller shaft load optimisation [6,79,80,83,84]
8	CO ₂ emissions reduction	Approximately 10–15% reduction depending on operating mode [6,77,78,80,82–84]	12–20% reduction through improved propulsion energy efficiency [6,78,79,82,83]
9	NO _x and SO _x emissions reduction	Up to 10–12% [77,78,80]	Up to 15–18% [6,79,80]
10	Impact on engine technical condition	Reduced engine wear through power limitation [6,77,78,80]	Shaft and propeller load optimisation; potential service life extension [6,79,80]
11	Logging and reporting requirements	Mandatory recording of power reserve utilisation [6,77,81,82]	Mandatory recording of power reserve utilisation including override events [6,79,81,82]
12	Management and safety	Simple control system; mechanical or electronic EPL [77–79]	More complex management with integration into propeller shaft control system [6,79]
13	Commercial limitations	May result in speed reduction and charter contract renegotiation [6,77,82]	Fewer commercial limitations owing to operational flexibility [6,77,82]
14	Potential cost savings	Up to 20% annual fuel savings compared to unrestricted operation [6,77,78,80,82–84]	Up to 25% savings possible through enhanced engine optimisation [6,79,80,83,84]

A comparative analysis of different types of power limiters demonstrates that mechanical systems, whilst simpler in design and operation, are inferior to electronic systems in terms of flexibility and regulation precision. Electronic limiters provide optimal integration with other shipboard systems and can be adapted to various operating modes, accounting for specific operational conditions and engine state. Combined systems represent a compromise solution that unites the reliability of mechanical and the flexibility of electronic limiters.

Temporary deactivation is permitted when vessel, crew, or environmental safety demands it—though the regulatory requirements governing documentation and notification of relevant authorities are strict. The result is a paper trail that port state control officers and classification surveyors can independently verify.

The procedure for re-activating power limitation systems following temporary deactivation is likewise subject to careful regulation and verification. The availability of objective evidence of the procedure—such as mechanical sealing, documentation in a dedicated engine power logbook, and photographic records—reflects the rigorous approach to monitoring compliance with environmental requirements.

In the context of the global decarbonization objectives for maritime transport—a 40% reduction in emissions by 2030 and 70% by 2050 relative to the 2008 baseline—power limitation must be regarded as one component of a comprehensive strategy. Used in isolation, neither EPL nor SHaPoLi is sufficient; their real value emerges when layered with slow steaming, hull optimization, and fuel switching.

An analysis of the characteristics of various fuel types demonstrates significant potential for decarbonization of the maritime sector. Methanol, with its lower carbon content (37.49%) compared to conventional diesel fuel (86.88%) and LNG (approximately 75%), is completely miscible with water and has zero sulfur content, making it a promising option for reducing pollution. Hydrogen, with zero carbon content and an exceptionally high calorific value (120 MJ/kg), represents a radical solution but faces challenges with respect to storage and transportation.

The economic implications of power limitation implementation warrant further analysis. Although the reduction in fuel consumption leads to direct cost savings, it is necessary to account for the installation and maintenance costs of EPL and SHaPoLi systems, as well as the potential impact on vessel operational efficiency. Balancing these factors is key to ensuring the economic viability of power limitation and decarbonization measures.

Japan's pilot programs—moving from LNG through recycled-carbon methane towards hydrogen and ammonia—suggest that no single fuel will dominate; a staged, technology-diverse pathway is the more realistic route to the 2050 targets. The integration of power limitation systems with innovative fuel technologies may produce a synergistic effect and maximize environmental benefits whilst optimizing economic costs.

Power limitation is not a silver bullet, but it is one of the few measures that can be retrofitted quickly and at modest cost—which gives it an outsized role in the near-term transition. Future research should be directed towards the optimization of EPL and SHaPoLi systems, their integration with other energy-saving technologies, and the transition to alternative fuels to achieve the maximum effect in reducing the carbon footprint of the sector.

Based on the research conducted, four key directions have been formulated for the successful implementation of maritime fleet decarbonization strategies:

- Real-time monitoring of fuel consumption and GHG emissions via integrated data systems, with outputs used directly to calibrate CII performance and flag deviations early.
- Development of a flexible fuel procurement policy that accounts for the price volatility of conventional and alternative energy carriers, the availability of bunkering capacity in various ports, and the possibility of diversifying the fuel portfolio to minimize economic risks and ensure continuity of operational activity.
- Establishment of long-term partnerships with ports for the joint development of alternative fuel bunkering infrastructure, including the construction of specialized terminals for LNG, methanol, ammonia, and hydrogen, which is critically important for scaling the transition to clean energy carriers.
- Comprehensive crew training and support for the safe and effective operation of new power limitation technologies, CPP management systems, alternative fuel bunkering procedures, and upgraded propulsion plants, without which none of the new technologies can be safely or effectively deployed.

5. Conclusions

Neither hardware power limiters nor alternative fuels alone can deliver the reductions IMO demands—the evidence consistently points to their combined deployment as the only viable path.

Mapping the interrelationships between energy, environmental, technical, and economic constraints reveals that these challenges reinforce one another—which is precisely why piecemeal solutions have so far fallen short.

The comprehensive comparative analysis of alternative fuels has identified the advantages and challenges associated with each energy carrier. Fuel selection depends on vessel type, trading region, bunkering availability, and the shipowner's financial position.

The analysis of contemporary energy consumption regulation technologies has revealed the significant advantages and limitations of different types of power limitation systems. It has been established that power limitation systems employing controllable pitch propellers (CPP) integrated with electronic remote-control systems provide the highest degree of flexibility in managing propulsive characteristics without altering engine rotational speed, which is critically important for maintaining optimal energy efficiency under variable operational conditions.

SHaPoLi outperforms EPL on fuel and CO₂ reduction. Its edge comes from direct control over propulsive power and the ability to adapt to sea state and loading in real time. The trade-off is cost: high-precision torque sensors, tachometers, and a full monitoring stack push capital expenditure considerably higher than a straightforward EPL retrofit. Combining power limitation systems with alternative fuels demonstrably enables a radical reduction in the carbon footprint of the maritime sector.

The economic analysis of power limitation system implementation has revealed the potential for achieving considerable operational cost savings, if capital investments and operational benefits are assessed in a balanced manner. Critical importance attaches to accounting for the potential impact of vessel speed reduction on commercial efficiency, which may necessitate renegotiation of charter contracts and voyage schedules.

Companies that act on these findings stand a realistic chance of meeting the IMO's 40% and 70% reduction targets for 2030 and 2050. Fuel savings of 20–25% are achievable. In a market where regulators and charterers alike are scrutinising emissions records, that combination of compliance and cost reduction is a genuine competitive asset.

Author Contributions: Conceptualization, O.P., T.S., S.G. and M.L.; methodology, O.P., T.S., S.G. and M.L.; software, V.L., R.K. and A.K.; validation, O.P., T.S., S.G. and M.L.; data curation, O.P., T.S., S.G. and M.L.; writing—original draft preparation, O.P., T.S., S.G., V.L., R.K. and A.K.; writing—review and editing, O.P., M.L., S.G., V.L., R.K. and A.K.; visualization, V.L., R.K. and A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. UNCTAD. *Review of Maritime Transport 2023: Towards a Green and Just Transition*; United Nations Conference on Trade and Development: Geneva, Switzerland, 2023.
2. IMO. *Initial IMO Strategy on Reduction of GHG Emissions from Ships*; International Maritime Organization: London, UK, 2018.

3. Bouman, E.A.; Lindstad, E.; Riialand, A.I.; Strømman, A.H. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping—A review. *Transp. Res. Part D Transp. Environ.* **2017**, *52*, 408–421. [CrossRef]
4. Tzu, F.-M.; Su, D.-T. Evaluation of carbon dioxide emission based on energy efficiency existing ship index during oceanographic navigation. *J. Oper. Oceanogr.* **2024**, *17*, 151–164. [CrossRef]
5. Hasan, S.M.R.; Karim, M. Energy efficiency design index baselines for ships of Bangladesh based on verified ship data. *Heliyon* **2022**, *8*, e10996. [CrossRef]
6. Kalajdžić, M.; Vasilev, M.; Momčilović, N. Assessment of energy efficiency for the existing cargo ships. *J. Marit. Sci.* **2022**, *23*, 33–46. [CrossRef]
7. Du, Z.; Chen, Q.; Guan, C.; Chen, H. Improvement and optimization configuration of inland ship power and propulsion system. *J. Mar. Sci. Eng.* **2023**, *11*, 135. [CrossRef]
8. Goolak, S.; Petrychenko, O.; Burmaka, I.; Vynohradova, A. The use of LNG as an alternative marine fuel: Conceptual requirements and safety measures. In Proceedings of the 28th International Scientific Conference Transport Means 2024, Kaunas, Lithuania, 2–4 October 2024; pp. 965–970. [CrossRef]
9. Petrychenko, O.; Levinskyi, M.; Goolak, S.; Lukoševičius, V. Prospects of Solar Energy in the Context of Greening Maritime Transport. *Sustainability* **2025**, *17*, 2141. [CrossRef]
10. Park, M.-H.; Yeo, S.; Kim, J.-H.; Choi, J.-H.; Lee, W.-J. Comprehensive review on recent progress in renewable and sustainable energy applications in shipping industry, and suggestions for future developments. *Renew. Sustain. Energy Rev.* **2026**, *225*, 116152. [CrossRef]
11. Traut, M.; Larkin, A.; Anderson, K.; McGlade, C.; Sharmina, M.; Smith, T. CO₂ abatement goals for international shipping. *Clim. Policy* **2018**, *18*, 1066–1075. [CrossRef]
12. Olmer, N.; Comer, B.; Roy, B.; Mao, X.; Rutherford, D. *Greenhouse Gas Emissions from Global Shipping, 2013–2015 Detailed Methodology*; International Council on Clean Transportation: Washington, DC, USA, 2017; pp. 1–38.
13. Awwalin, R.; Saktiono, M.A.; Marsudi, S.; Tambun, R.; Suwasono, B.; Sutiyo. Trim Optimization for Ship Resistance Reduction and Energy Efficiency Existing Ship Index (EEI) Regulation Assessment. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2025; Volume 1473, p. 012029. [CrossRef]
14. Yang, B.; Liu, B.; Zhou, H.; Wang, J.; Yao, W.; Wu, S.; Shu, H.; Ren, Y. A critical survey of technologies of large offshore wind farm integration: Summary, advances, and perspectives. *Prot. Control Mod. Power Syst.* **2022**, *7*, 17. [CrossRef]
15. Balcombe, P.; Brierley, J.; Lewis, C.; Skatvedt, L.; Speirs, J.; Hawkes, A.; Staffell, I. How to decarbonise international shipping: Options for fuels, technologies and policies. *Energy Convers. Manag.* **2019**, *182*, 72–88. [CrossRef]
16. Sardar, A.; Anantharaman, M.; Islam, T.M.R.; Garaniya, V. Data collection framework for enhanced carbon intensity indicator (CII) in the oil tankers. *Can. J. Chem. Eng.* **2025**, *103*, 170–187. [CrossRef]
17. Gianni, M.; Pietra, A.; Coraddu, A.; Taccani, R. Impact of SOFC power generation plant on carbon intensity index (CII) calculation for cruise ships. *J. Mar. Sci. Eng.* **2022**, *10*, 1478. [CrossRef]
18. A.P. Møller-Mærsk A/S. *2018 Sustainability Report*; A.P. Møller-Mærsk A/S: Copenhagen, Denmark, 2018. Available online: https://www.maersk.com/media_sc9/maersk/corporate/sustainability/files/resources/2018/apmm-sustainability-report-2018-a3_190228.pdf (accessed on 7 March 2026).
19. Adamowicz, M. Decarbonisation of maritime transport—European Union measures as an inspiration for global solutions? *Mar. Policy* **2022**, *145*, 105085. [CrossRef]
20. Skjong, S.; Pedersen, E. A distributed object-oriented simulator framework for marine power plants with weak power grids. *J. Mar. Eng. Technol.* **2023**, *22*, 176–188. [CrossRef]
21. Khare, V.; Bhuiyan, M.A. Tidal energy-path towards sustainable energy: A technical review. *Clean. Energy Syst.* **2022**, *3*, 100041. [CrossRef]
22. Zis, T.P. Prospects of cold ironing as an emissions reduction option. *Transp. Res. Part A Policy Pract.* **2019**, *119*, 82–95. [CrossRef]
23. Wu, P.C.; Lin, C.Y. Feasibility and cost-benefit analysis of methanol as a sustainable alternative fuel for ships. *J. Mar. Sci. Eng.* **2025**, *13*, 973. [CrossRef]
24. Sagin, S.V.; Sagin, S.S.; Fomin, O.; Gaichenia, O.; Zablotskyi, Y.; Píšťek, V.; Kučera, P. Use of biofuels in marine diesel engines for sustainable and safe maritime transport. *Renew. Energy* **2024**, *224*, 120221. [CrossRef]
25. Lee, H.; Lee, J.; Roh, G.; Lee, S.; Choung, C.; Kang, H. Comparative life cycle assessments and economic analyses of alternative marine fuels: Insights for practical strategies. *Sustainability* **2024**, *16*, 2114. [CrossRef]
26. Ha, S.; Jeong, B.; Jang, H.; Park, C.; Ku, B. A framework for determining the life cycle GHG emissions of fossil marine fuels in countries reliant on imported energy through maritime transportation: A case study of South Korea. *Sci. Total Environ.* **2023**, *897*, 165366. [CrossRef]
27. Machaj, K.; Kupecki, J.; Malecha, Z.; Morawski, A.W.; Skrzypkiewicz, M.; Stanlik, M.; Chorowski, M. Ammonia as a potential marine fuel: A review. *Energy Strategy Rev.* **2022**, *44*, 100926. [CrossRef]

28. Huang, J.; Fan, H.; Xu, X.; Liu, Z. Life cycle greenhouse gas emission assessment for using alternative marine fuels: A very large crude carrier (VLCC) case study. *J. Mar. Sci. Eng.* **2022**, *10*, 1969. [[CrossRef](#)]
29. Zhou, Z.; Tao, J. Hydrogen-powered vessels in green maritime decarbonization: policy drivers, technological frontiers and challenges. *Front. Mar. Sci.* **2025**, *12*, 1601617. [[CrossRef](#)]
30. Teoh, Y.H.; How, H.G.; Le, T.D.; Nguyen, H.T.; Loo, D.L.; Rashid, T.; Sher, F. A review on production and implementation of hydrogen as a green fuel in internal combustion engines. *Fuel* **2023**, *333*, 126525. [[CrossRef](#)]
31. Mouchane, B.; Baştürk, S. Optimum design of liquefied petroleum gas (LPG) composite hybrid and non-hybrid cylinders by genetic algorithm for maximum failure pressure. *Int. J. Mech. Mater. Des.* **2025**, *21*, 1643–1667. [[CrossRef](#)]
32. EL Fakkoussi, S.; Gouzi, M.B.; Elkhalfi, A.; Vlase, S.; Scutaru, M.L. Integrate the Isogeometric Analysis Approach Based on the T-Splines Function for the Numerical Study of a Liquefied Petroleum Gas (LPG) Cylinder Subjected to a Static Load. *Appl. Sci.* **2025**, *15*, 3102. [[CrossRef](#)]
33. Psaraftis, H.N.; Kontovas, C.A. Decarbonization of maritime transport: Is there light at the end of the tunnel? *Sustainability* **2020**, *13*, 237. [[CrossRef](#)]
34. Nanda, M.I.; Gurning, R.O.S. Development of Web Programming for Calculation of Energy Efficiency Design Index (EEDI). *Revolution* **2022**, *4*, 160–168. [[CrossRef](#)]
35. Braidotti, L.; Bertagna, S.; Rappoccio, R.; Utzeri, S.; Bucci, V.; Marinò, A. On the inconsistency and revision of Carbon Intensity Indicator for cruise ships. *Transp. Res. Part D Transp. Environ.* **2023**, *118*, 103662. [[CrossRef](#)]
36. Caciagli, V. Emission trading schemes and carbon markets in the NDCs: their contribution to the Paris agreement. In *Theory and Practice of Climate Adaptation*; Springer International Publishing: Cham, Switzerland, 2018; pp. 539–571. [[CrossRef](#)]
37. Kolodziejski, M.; Michalska-Pozoga, I. Battery energy storage systems in ships' hybrid/electric propulsion systems. *Energies* **2023**, *16*, 1122. [[CrossRef](#)]
38. Tsvetanov, D. Supraharmonics in shipboard power systems: research gaps, challenges, and future directions. *J. Mar. Eng. Technol.* **2026**, *2026*, 261890. [[CrossRef](#)]
39. Ishaq, M.; Ullah, K.; Abbass, M.J.; Awais, M. Reactive power compensation applications of matrix converter: a systemic review. *Eng. Res. Express* **2024**, *6*, 042301. [[CrossRef](#)]
40. Fikir, E.; Nuran, M. Enhancement of Reactive Power and Efficiency Using Hybrid Compensation Approach for Supply Vessels. *J. Mar. Sci. Eng.* **2026**, *14*, 463. [[CrossRef](#)]
41. Alkhafaji, M.H. Optimal and Stable Framework for Robust Field-Oriented Control of PMSM using Hybrid ALO-MRSO. *Eur. J. Electr. Eng. Comput. Sci.* **2025**, *9*, 50–58. [[CrossRef](#)]
42. Karakatsanis, T.S. Optimization and Performance Evaluation of PM Motor and Induction Motor for Marine Propulsion Systems. *Appl. Syst. Innov.* **2025**, *8*, 58. [[CrossRef](#)]
43. Pribadi, W.; Wicaksono, R.Y.; Putra, R.G.; Wicaksono, D.A.; Yazid, M.L. Artificial intelligence for field-oriented control on light rail transit Jabodebek. *J. Mechatron. Electr. Power Veh. Technol.* **2025**, *16*, 106–118. [[CrossRef](#)]
44. Demirel, H.; Karadağ, M.; Başhan, V.; Mutlu, Y.T.; Kaya, C.; Gul, M.; Akyuz, E. Hybrid Neutrosophic Fuzzy Multi-Criteria Assessment of Energy Efficiency Enhancement Systems: Sustainable Ship Energy Management and Environmental Aspect. *Sustainability* **2025**, *18*, 166. [[CrossRef](#)]
45. Hadi, I.; Yola, L.; Hanifa, A.S.; Muzhaffar, M.H. Decarbonization Strategy towards Net Zero Emission for International Shipping on International Shipping Routes in Indonesian Archipelago Sea Lanes. *Int. J. Technol.* **2025**, *16*, 8–26. [[CrossRef](#)]
46. Tsimplis, M. Emission Reduction from Shipping and Net-Zero Shipping: Institutional Deficiencies and the Way Forward. In *The South China Sea: The Geo-Political Epicenter of the Indo-Pacific*; Springer Nature: Singapore, 2025; pp. 131–146. [[CrossRef](#)]
47. Bayraktar, M.; Mollaoglu, M.; Yuksel, O. Scientometric Analysis of Energy Efficiency Indicators in Maritime Transportation: A Systematic State-of-the-Art Review and Implications. *Sustainability* **2025**, *17*, 3612. [[CrossRef](#)]
48. Zhao, Y.; Wen, S.; Zhao, Q.; Zhang, B.; Huang, Y. Deep reinforcement learning-based energy management strategy for green ships considering photovoltaic uncertainty. *J. Mar. Sci. Eng.* **2025**, *13*, 565. [[CrossRef](#)]
49. Yuksel, O.; Blanco-Davis, E.; Spiteri, A.; Hitchmough, D.; Shagar, V.; Di Piazza, M.C.; Pucci, M.; Tsoulakos, N.; Armin, M.; Wang, J. Optimising the design of a hybrid fuel cell/battery and waste heat recovery system for retrofitting ship power generation. *Energies* **2025**, *18*, 288. [[CrossRef](#)]
50. Champion, M.; Dalla Preda, M.; Giacobazzi, R.; Urban, C. A logic for the imprecision of abstract interpretations. *Proc. ACM Program. Lang.* **2026**, *10*, 1876–1904. [[CrossRef](#)]
51. Xu, Y.; Chai, Z.; Meng, X.; Xu, Y.; Sun, J.; Zhou, P. Silicon Nitride-Photonics-Enabled Optical Pumping for Optically Pumped Magnetometer. *Laser Photonics Rev.* **2025**, *19*, 2402292. [[CrossRef](#)]
52. Wang, Y.; Li, J. Multi-criteria decision-making for green maritime transportation: A hybrid Fuzzy AHP-MOORA approach to reduce marine pollution. *Mar. Pollut. Bull.* **2025**, *216*, 118023. [[CrossRef](#)]
53. Sontakke, I.; Bergström, M.; Gosala, V.; Baldauf, M.; Ehlers, S. Techno-economic analysis of decarbonization pathways for a deep-sea container vessel. *Ship Technol. Res.* **2025**, *2025*, 2585247. [[CrossRef](#)]

54. Fu, W.; Lu, W.; Liu, H.; Yuan, X.; Zeng, D. Smooth braking control of excavator hydraulic load based on command reshaping. *ISA Trans.* **2025**, *158*, 674–685. [[CrossRef](#)]
55. Zachepa, I.; Chenchvoi, V.; Zachepa, N.; Chenchva, O.; Serhienko, S. Study of a local source of autonomous power supply on the basis of a diesel generator. *EUREKA Phys. Eng.* **2022**, *6*, 56–73. [[CrossRef](#)]
56. Nash, J.; Sauv , K.; van Riet, C.M.; van Oosterhout, A.; Sharma, A.; Clarke, C.; Alexander, J. HydroHaptics: High-Fidelity Force-Feedback on Soft Deformable Interfaces using Hydrostatic Transmission. In Proceedings of the 38th Annual ACM Symposium on User Interface Software and Technology, Busan, Republic of Korea, 28 September 2025–1 October 2025; pp. 1–20. [[CrossRef](#)]
57. Gorb, S.; Popovskii, A.; Budurov, M. Adjustment of speed governor for marine diesel generator engine. *Int. J. GEOMATE* **2023**, *25*, 125–132. [[CrossRef](#)]
58. Liu, S.; Liu, Z.; Li, Y.; Wu, D.; Zhao, H. Research on Position-Feedback Control Strategy of Engineered Drilling Rig Hydro-Mechanical Composite Propulsion System. *Processes* **2025**, *13*, 2470. [[CrossRef](#)]
59. Kitagawa, Y.; Bondarenko, O.; Tsukada, Y.; Fukuda, T.; Tanizawa, K. An application of the tank test with a model ship for design of ship propulsion plant system. *Mar. Eng.* **2018**, *53*, 355–361. [[CrossRef](#)]
60. Yuan, H.; Lam, H.S.; Liang, G.; Tan, S.C.; Pou, J.; Hui, S.Y.R. Fault-tolerant control of electric-spring enabled solid-state transformer under dual active bridge failure. *IEEE J. Emerg. Sel. Top. Power Electron.* **2023**, *12*, 118–128. [[CrossRef](#)]
61. Silvestro, F.; D’Agostino, F.; Schiapparelli, G.P.; Boveri, A.; Patuelli, D.; Ragaini, E. A collaborative laboratory for shipboard microgrid: Research and training. In *2018 AEIT International Annual Conference*; IEEE: New York, NY, USA, 2018; pp. 1–6. [[CrossRef](#)]
62. Oluwalana, O.J.; Grzesik, K. Solar-powered electric vehicles: comprehensive review of technology advancements, challenges, and future prospects. *Energies* **2025**, *18*, 3650. [[CrossRef](#)]
63. Barnes, S.; Georgadze, A.; Giammanco, A.; Kiisk, M.; Kudryavtsev, V.A.; Lagrange, M.; Pinto, O.L. Cosmic-ray tomography for border security. *Instruments* **2023**, *7*, 13. [[CrossRef](#)]
64. Al-Hraishawi, H.; Chougrani, H.; Kisseleff, S.; Lagunas, E.; Chatzinotas, S. A survey on nongeostationary satellite systems: The communication perspective. *IEEE Commun. Surv. Tutor.* **2022**, *25*, 101–132. [[CrossRef](#)]
65. Asral, A.; Nurhidayat, M.; Herisiswanto, H.; Afrizal, E.; Hafis, M.H.; Samad, R.; Muhammadu, M.M. Performance Evaluation of Fixed Pitch Propellers: Flow Visualization of Cavitation in Unmanned Surface Vehicles. *J. Ocean Mech. Aerosp.-Sci. Eng.* **2025**, *69*, 91–98. [[CrossRef](#)]
66. Yurtseven, A.; Aktay, K. The numerical investigation of spindle torque for a controllable pitch propeller in feathering maneuver. *Brodogr. Int. J. Nav. Archit. Ocean Eng. Res. Dev.* **2023**, *74*, 95–108. [[CrossRef](#)]
67. Gypa, I.; Jansson, M.; Gustafsson, R.; Werner, S.; Bensow, R. Controllable-pitch propeller design process for a wind-powered car-carrier optimising for total energy consumption. *Ocean Eng.* **2023**, *269*, 113426. [[CrossRef](#)]
68. Tian, W.; Lang, X.; Zhang, C.; Yan, S.; Li, B.; Zang, S. Optimization of controllable-pitch propeller operations for yangtze river sailing ships. *J. Mar. Sci. Eng.* **2024**, *12*, 1579. [[CrossRef](#)]
69. Zhao, W.; Guan, H.; Shu, S. Research on wireless dynamic variable pitch propeller control system. In *2025 International Conference on Aerospace Information Perception and Intelligent Processing (AIPIP)*; IEEE: New York, NY, USA, 2025; pp. 354–360. [[CrossRef](#)]
70. Zhang, Z.; Zhang, Y.; Yu, J.; Du, P.; Zhao, J. Variable Pitch Propeller: Multi-Objective Optimization Design and Performance Analysis. *Eng. Proc.* **2025**, *80*, 36. [[CrossRef](#)]
71. Naoki, Y.; Nagai, S.; Fujimoto, H. Mode-switching algorithm to improve variable-pitch-propeller thrust generation for drones under motor current limitation. *IEEE/ASME Trans. Mechatron.* **2023**, *28*, 2003–2011. [[CrossRef](#)]
72. Candelo-Beccera, J.E.; Maldonado, L.B.; Sanabria, E.P.; Pestana, H.V.; Garc a, J.J. Technological alternatives for electric propulsion systems in the waterway sector. *Energies* **2023**, *16*, 7700. [[CrossRef](#)]
73. Erc3000-Propulsion Control System. Available online: <https://www.scribd.com/document/712759116/ERC3000-PROPULSION-CONTROL-SYSTEM> (accessed on 10 November 2025).
74. Maalawi, K.Y.; Nasr, M.F.; EL-Bayoumi, M.A. A novel concept for multi-objective optimization of composite power transmission shafts. *J. Braz. Soc. Mech. Sci. Eng.* **2024**, *46*, 449. [[CrossRef](#)]
75. Garbatov, Y.; Georgiev, P. Advances in the prevention of shipping-related air pollution. *Energies* **2024**, *17*, 5991. [[CrossRef](#)]
76. Polemis, D.; Boviatsis, M.; Chatzinikolaou, S. Assessing the sustainability of the Most prominent type of marine diesel engines under the implementation of the EEXI and CII regulations. *Clean Technol.* **2023**, *5*, 1044–1066. [[CrossRef](#)]
77. Costache, A.; Bosoanc , R. Engine power limitation (EPL) to comply with EEXI requirements. Study on an LPG tanker. *Ann. “Dunarea De Jos” Univ. Galati Fascicle XI—Shipbuild.* **2024**, *47*, 65–74. [[CrossRef](#)]
78. Kocak, G.; Durmusoglu, Y. Exergy efficiency and EEXI analysis of a marine power plant at partial load conditions. *Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ.* **2024**, *238*, 543–552. [[CrossRef](#)]
79. Paun, I.A.; Bosoanc , R. The reduction of the main engine’s power for a 15000 tdw chemical tanker regarding the achievement of EEXI and its influence on manoeuvrability. *Ann. “Dunarea De Jos” Univ. Galati Fascicle XI—Shipbuild.* **2024**, *47*, 75–82. [[CrossRef](#)]

80. Ammar, N.R.; Almas, M.; Nahas, Q. Economic analysis and the EEXI reduction potential of parallel hybrid dual-fuel engine-fuel cell propulsion systems for LNG carriers. *Pol. Marit. Res.* **2023**, *30*, 59–70. [[CrossRef](#)]
81. Schroer, M.; Panagakos, G.; Barfod, M.B. An evidence-based assessment of IMO's short-term measures for decarbonizing container shipping. *J. Clean. Prod.* **2022**, *363*, 132441. [[CrossRef](#)]
82. Czermański, E.; Oniszczyk-Jastrzębek, A.; Spangenberg, E.F.; Kozłowski, Ł.; Adamowicz, M.; Jankiewicz, J.; Cirella, G.T. Implementation of the Energy Efficiency Existing Ship Index: An important but costly step towards ocean protection. *Mar. Policy* **2022**, *141*, 105259. [[CrossRef](#)]
83. Lee, S.-S. Analysis of the effects of EEDI and EEXI implementation on CO₂ emissions reduction in ships. *Ocean Eng.* **2024**, *297*, 116877. [[CrossRef](#)]
84. Rutherford, D.; Mao, X.; Osipova, L.; Comer, B. *Limiting Engine Power to Reduce CO₂ Emissions from Existing Ships*; International Council on Clean Transportation: Washington, DC, USA, 2020. Available online: https://theicct.org/sites/default/files/publications/Limiting_engine_power_02112020_0.pdf (accessed on 15 December 2025).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.