Volume XXIX 2026
MBNA Publishing House Constanta 2026

Scientific Bulletin of Naval Academy

SBNA PAPER • OPEN ACCESS

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To cite this article: Aleksandar Hristov and Irina Dilova, Scientific Bulletin of Naval Academy, Vol. XXIX 2026, pg. 8-18.

Submitted: 24.04.2026
Revised: 31.07.2026
Accepted: 04.08.2026

Available online at www.anmb.ro

ISSN: 2392-8956; ISSN-L: 1454-864X

doi: 10.21279/1454-864X-26-I1-001

Energy Efficiency Measures vs. Biofuels - Implications for Vessel Operational Performance

Aleksandar Hristov[1,*], Irina Dilova[2]

[1]Nikola Vaptsarov Naval Academy, Navigation Faculty, 241741@naval-acad.bg
[2]Nikola Vaptsarov Naval Academy, Navigation Faculty, 241746@naval-acad.bg

Abstract. The purpose of this study is to determine the relative importance of energy saving measures (ESMs) and alternative biofuels for the improvement of ship efficiency and for compliance with new regulations imposed on the maritime transport sector. In light of the fact that ESMs have proven that they are capable of providing a significant fuel saving potential by enhancing the hull condition, propulsion, and internal combustion efficiency as well as through operational optimization, the aim of this study is to investigate the advantages and disadvantages of ESMs compared to biofuels. To this end, a mixed methodological approach was applied, based on the structured analysis of scientific literature, and complemented by semi-structured interviews with maritime engineers, fleet managers, fuel specialists and regulatory experts. The findings show that ESMs provide on average a proven and reliable energy and emissions saving potential, although the degree of this saving potential varies from one measure to another, depending on their complexity, cost and degree of integration. Each of the biofuels examined presents different operational characteristics, as one has a high regulatory value, although it is relatively unstable in deep sea conditions, while the other presents good storage characteristics and engine performance but with limited market availability and high price. Finally, ESMs seem to be the most effective solutions for the improvement of ship efficiency, while the alternative biofuels examined could be considered as part of the compliance strategy of shipowners in cases where their operational characteristics are taken into account.
Keywords: Operational efficiency; Vessel performance; Energy efficiency measures; Biofuels.

1. Introduction

The maritime industry is undergoing a fundamental change at a rapid pace due to increasing regulations, high costs of compliance and the need for optimizing energy efficiency on a fleet level. Combined with the new IMO GHG Strategy aiming for achieving net-zero greenhouse gas emissions by (or around) 2050 with interim milestones for 2030 and 2040, there is a clear focus on on energy efficiency of the vessels, alternative low carbon fuels and readiness of ships for future retrofits of alternative low carbon propulsion technologies (Wang & Wright, 2021). At the same time, the European Union has adopted the most ambitious decarbonisation policy ever adopted for the maritime sector so far. Under the EU Emissions Trading System (EU ETS), shipping companies will need to buy emission allowances for the verified CO2 emissions from 2024 onwards. As a result, ship owners will incur a financial penalty for the CO2 they emit and the costs associated with this will be built into the voyage economics, the time charter equivalent (TCE) and other long term investment decisions. Estimates from recent analyses indicate that the ETS-induced carbon costs may account for between 8-25% of the total voyage costs, depending on the type and size of the vessel, on the shipping route and on the market situation at the time (Lee et al., 2024). A second key piece of the puzzle, FuelEU Maritime, which were applied from 2025 with stepwise reductions in the GHG intensity of onboard fuel use for engines. This also includes a package of penalties and incentives aimed to enforce the uptake of biofuels and e-fuels in the short and medium term. Recent assessments now also assume a more rapid market entry of drop-in alternatives such as HVO and advanced FAME variants, because their use will allow vessel operators to comply with the new limit value in the short term and without any complex or cost-reflective modifications or conversions to engines (Prussi et al., 2021).

Except for the regulations mentioned above, the shipping industry has to contend with many operational and market factors that affects the efficiency and competitiveness of the industry. The global shipping market forecast has shown that the maritime transport is set to increase steadily in the coming years with the world seaborne trade growing, demanding more and more fuel while having to comply with ever stricter technical and operational performance levels (Naghash et al., 2024). As a consequence, shipping companies have to introduce measures to reduce fuel consumption and carry out a high level of maintenance for their assets and operations, and to optimise their voyages and management of their fleet. In this context the measures of MRV/DCS are increasingly adding more key performance indicators such as the CII or the EEXI, which are having a more significant influence on operational decisions, on market access during the chartering procedures and on the commercial value of the vessel. Research have also shown that the increase of the CII of a large part of the global fleet, including those being regulated, could expose inefficient vessels to higher compliance and reputational costs and may reduce their competitive position on the market. This is also applicable to non-regulated ships. Indeed, the non-compliance of certain fleets in the management of their efficiency indicators could bring not only regulatory costs but also penalisation during chartering or financial losses on the sale of less efficient assets (Wu et al., 2022). In today's Framework environment, the strategic dilemma between energy-efficiency measures (EEMs) and biofuels is no longer a technological issue, but rather an operational and economic decision-making issue, which is central to the management of the fuels strategy of a vessel operator in order to address regulatory requirements, minimize costs and ensure the future viability of the fleet.

The operational efficiency of vessels in the maritime sector is generally understood as a multi-dimensional factor involving **technical, environmental** and **economic** performance. From a technical point of view, operational efficiency concerns the technical capabilities of the vessel to transport goods in a manner which provides the highest possible transport capacity in relation to energy input while maintaining low levels of energy loss, thereby preventing a deterioration in the condition of the hull, optimising the propulsion system, ensuring proper operation of mechanical systems, and adhering to load, including a controlled speed regime, and to regular maintenance and associated operations. Environmentally, operational efficiency is linked to the consumption of fuel, the level of emissions, the extent of compliance with regulations, the implementation of the CII and the possible imposition of regional carbon-pricing mechanisms and fuel-based requirements. From an economic perspective, the factor of operational efficiency is considered in the context of competitive costs of the vessel for cargo owners or lessors and is associated with fuel efficiency, maintenance requirements of the main engines and auxiliaries and voyage optimisation as well as charges for carbon emissions; elements which all have an impact on the costs related to operational activities and the efficiency of the charter agreements and rates. This triad provides the analytical framework for evaluating both energy efficiency measures and biofuels in the present study, enabling a systematic comparison of their physical, regulatory and cost implications.

Shipping has been dealing with a major strategic decision over the last couple of years and this will continue for years to come. Shipowners and operators have to decide whether to invest in technology and operational energy efficiency measures (EEMs) or whether to switch to alternative fuels such as biofuels. The choices presented with these two alternatives are fundamentally different and the operational consequences will also vary significantly. Energy efficiency measures (EEMs) mainly focus on the Tank-to-Wake efficiency, by reducing ship fuel consumption by optimizing hull and propeller design, reducing ship speed and trim, by imposing shaft power limits, and also through predictive maintenance. Available literature states that fuel consumption can be reduced by between 5 and 20 %. However, a number of measures have been identified which may either contradict other benefits or present the engine with additional challenges, for example, slow steaming may affect maintenance cycles and long-term engine reliability due to the need for more frequent idling to maintain engine performance when operating under low load. (Farkas et al., 2022). In summary, EEMs are not what you might term "free efficiency" as they simply re-arrange the load and the associated risk. Biofuels mainly affect the Well-to-Wake carbon footprint with the potential for lower lifecycle greenhouse gas emissions and an overall lower carbon footprint. However, the operational aspects are not as straightforward. When considering bio-fuels such as FAME (Fatty Acid Methyl Ester) also widely known as vegetable oil methyl ester, there are a number of known issues that can impact the dependability of equipment and lead to increased number of unscheduled repairs. These include hygroscopicity (water attraction) oxidation, microbial growth, fuel instability and material incompatibility (Faitar et al., 2025). Especially with regards to more stable fuels such as HVO, the combustion characteristics and SFOC can differ under a variety of operating conditions. In such cases, even though emissions performance may be improved, fuel efficiency has not necessarily been enhanced (Tu et al., 2024).

There is a significant conceptual contradiction between the sectors of industry and academia in relation to biofuels and EEMs (Energy Efficiency Measures) comparisons. In fact, whereas energy efficiency measures are compared on a short-term basis based on energy saving, efficiency and performances (Tank-to-Wake), biofuels are evaluated on the basis of the overall sustainability and compliance potential, from a lifecycle perspective (Well-to-Wake). In this case the most advantageous solution appears to depend on the criteria used for comparison (Zamboni et al., 2024). Comprehensive investigations regarding the operational effects of different alternative fuels on marine engines are lacking, whereas there are numerous papers examining the characteristics of various alternative fuels through comparative studies. While these studies usually have a strong focus on exhaust gas emissions and production processes, the relations of the fuel characteristics to the key operational performance indicators, such as engine reliability, maintenance, spare parts consumption, safety and handling, have not been investigated in a systematic way. Consequently, today the ship operators do not have a possibility of having a unified and common basis to assess the operational consequences of different alternative fuels on their ships (Robalo-Cabrera et al., 2025).

The scope of the publication is to present, in a structured and evidence-based manner, the comparison between different Energy-Efficiency Measures (EEMs) and biofuels to evaluate alternative ways to enhance the operational efficiency of maritime transport. Specifically, the assessment is based on four pillars that take into account all relevant aspects of operational efficiency such as:

1. the technical, economic and environmental aspects ,
2. the costs (CAPEX,OPEX),
3. the ability to comply with regulations implemented by the IMO and the EU,
4. the technical readiness level, reliability and applicability of existing measures.

It aims to support shipowners with the choices they will have to face in the context of the ongoing shift towards low carbon shipping.

2. Materials and methods

The research applies two qualitative methods focusing on different aspects of operational efficiency improvements in maritime transport:

- **a** systematic literature review**,** and
- **semi-structured expert interviews**.

2.1. Systematic Literature Review

A structured literature review was conducted across Scopus, Web of Science, ScienceDirect, and MDPI databases, covering the period 2015–2025. The review focused on four categories of sources:The literature review focuses on key topics such as:

- studies on energy-efficiency measures and their technical and operational performance effects;
- analyses of biofuels, especially FAME, HVO, with focus on engine compatibility and operational reliability;
- research on regulatory frameworks such as IMO CII/EEXI, EU ETS, and FuelEU Maritime;
- publications evaluating technological readiness (TRL) and decarbonization scenarios.

In total, **82 peer-reviewed sources** were found, of which **41** met the inclusion criteria (operational relevance, empirical data, and clear methodology). The review informed the comparative framework and provided the conceptual basis for assessing performance, cost, and regulatory alignment. Similar structured approaches to evaluating operational and managerial factors in logistics systems have been discussed in previous studies (Stefanova, 2022).

2.2. Semi-Structured Expert Interviews

To complement the theoretical insights, semi-structured interviews were conducted with maritime professionals possessing direct operational knowledge of both EEMs and biofuels. The expert panel included:

- technical superintendents and fleet managers (4),
- chief engineers with biofuel experience (3),
- bunker suppliers and fuel quality specialists (2),
- regulatory/compliance experts (1).

Interviews lasted between 35 and 60 minutes and were carried out in person and via online conferencing platforms. The interview guide covered:

- operational performance and reliability of EEMs;
- practical challenges of using FAME, HVO, and bio-methanol;
- cost and maintenance implications;
- regulatory compliance strategies under CII, ETS, and FuelEU Maritime;
- projections for the next decade in terms of fuel choice and technology adoption.

All interviews were transcribed verbatim and analyzed through thematic coding, which enabled the identification of recurring patterns and divergences. The triangulation of findings from literature and interviews strengthens the robustness of the comparative assessment and ensures that the analysis reflects both scientific evidence and real-world operational realities.

3. Results

3.1. Energy Efficiency Measures (EEMs)

3.1.1. Literature review (evidence synthesis and measure-level differentiation)

Currently, the literature considers EEMs as the most mature opportunity for reducing the Tank-to-Wake potential of ships as they act on the largest number of variables directly affecting the performance of the ship. The fuel can be saved at the hull, propeller, machinery and operational level, by means of an infinity of possibilities that consist on the reduction of the resistances, the improvement of the efficiency of the ship at design and off design conditions, as well as in the reduction of the auxiliaries consumptions. Moreover, and regardless of the approach used (empirical or numerical), hull and propeller surface roughness, bad propulsor design, poor operation at part load, inefficiencies in powering auxiliary systems are identified as the main sources of the energy losses that EEMs are trying to save over time and therefore having a direct impact on the key performance indicators of the ship performance.

The analysis by Tadros et al. strongly suggests that hull condition management (painting, surface roughness control, anti-fouling) is a high-leverage measure. The authors show that hull and propeller surface roughness affects the lost power and the resulting reduced fuel efficiency over time, and that the impact can amount to several percent which is a non-negligible effect for long voyages (Tadros et al., 2023). The work by Zeng et al. also demonstrated through complex numerical simulations and data obtained onboard, that localised surface roughness resulting from inadequate surface preparation prior to applying paints, or between maintenance operations, increases the resistance and hence, the energy lost (Zeng et al., 2025). These recent studies tend to confirm strongly that “surface condition” is not a secondary factor but is in fact, a dominant factor in ships’ original efficiency. This is a particularly strong message for hull condition management since the measures required to maintain the ship’s surface in good condition are particularly effective and appear to be intrinsically stable. In other words, the resistance losses due to a rougher hull and propeller are due to friction rather than to any aspect related to the operational characteristics of the ship; and so are totally independent of crew performance, and therefore only depend on the ship’s maintenance activities.

Moderate and predictable benefits are commonly reported in the literature for propeller retrofits and Energy Saving Devices (ESDs). The importance of a holistic analysis of the propulsion system is also repeatedly stressed. In particular, a dedicated computational fluid dynamics (CFD) investigation into propeller retrofit potential was carried out by Tan et al. to examine the benefits of fitting propeller boss cap fins (PBCF) and to demonstrate the importance of considering any energy saving from such modifications in conjunction with hull–engine–propeller matching (i.e. not as a "bolt-on" improvement to the existing hull propulsion system) (Tan et al., 2023). Stark et al. also recently summarised potential ESD benefits when used on their own or in combination and identified key areas for design and application and hence where benefits are maximised and/or when potential interactions or reduced benefits may be expected. (Stark et al., 2022). In general, all of these works indicate that propeller retrofits/changes can achieve realisable benefits but the effectiveness of such measures are very design-dependent i.e. an optimised retrofit for one hull, in one particular flow condition, will likely deliver very different energy-saving performance on a different hull, with a different wake field.

Slow steaming is probably still the most debated operational tactic and is associated with the largest quantity of theoretical fuel savings, but it causes second-order effects which can in some cases be not negligible. In Farkas et al. study on containerships is presented dealing with the possibility of slow steaming when compliance with regulatory fuel efficiency is demanded, and that low speed operation can be the cause of some maintenance and operational issues, like hull fouling due to not perfect combustion, aging of auxiliary engines etc, thus partly penalizing any achieved "fuel saving" (Farkas et al., 2022). Very recently Degiuli et al. also assume that reduction in speed is a means to reach a reduction in emissions. However they focus on the operational trade-offs resulting from such a reduction, by highlighting the consequence of more time spent at lower speeds and potential losses associated with off-design operation (Degiuli et al., 2024). High-effect, but context dependent in general, slow steaming is characterised as high-effect but context dependent. The level of impact may vary depending on the engine characteristics, as well as on charter-party clauses and maintenance requirements.

3.1.2. Expert interview results (operational validation, divergences, and "what actually works")

All of the interviews confirmed the literature's main finding that EEMs lead to the largest Tank-to-Wake reductions but that they also highlight the distinction between "paper savings" and "bankable savings". By applying thematic coding to comments from superintendents, fleet managers, chief engineers, bunker/fuel-quality specialists and compliance expert we gain an insight into the factors influencing the implementation of EEMs, seen through the operational lenses of: (i) measurability, (ii) reliability and maintenance burden, and (iii) interference with commercial operations.

Strong consensus: hull and propeller condition management is the highest-confidence measure.

Hull maintanance (coat condition, window cleaning and anti biofouling maintenance) was a recurring theme during interviews across the technical-management group, with fuel efficiency benefits derived from such maintenance being seen as the lowest risk and thus the baseline or "business as usual". It is possible that this is an intrinsic feature of hull maintenance and that the hull roughness "evidence base" of resistance penalties which grow in magnitude over time has a bearing on this view. Additionally that hull derivative performance changes do not impinge on the engines operating envelope.

Conditional agreement: propulsion retrofits are effective only when engineered to the specific ship. Both a superintendent and a fuel quality specialist agreed that ESDs and propeller retrofits offered potential gains on a stable basis; however, they refused to accept what they called "catalogue thinking". The second group indicated that wake-field characterization and retrofit verification by measurement were required to support any predictions of engine efficiency improvement. Without such characterization and verification, the potential for improvement was reduced to the level of a prediction or guess. Their practitioner stance is therefore opposed to the integrated matching concept in the propeller retrofit literature.

Clear divergence: slow steaming is viewed as both powerful and operationally risky.

Fleet-management and chief engineers gave markedly different views on the impact of a proposed worldwide speed reduction for ships to mitigate their part of the reduction strategy for reductive carbon emissions. The management group argued for the speed reduction due to the speed with which it could lead to a reduction in fuel consumption and associated regulatory issues. Furthermore, it was easy to argue in favour of the reduction at a time when charter-party conditions generally supported such a move. Conversely, the chief engineers were largely opposed to the low-speed operation on the account of increased fouling and poorer combustion efficiency, as well as increased maintenance. In this respect the low-speed measure was 'highly effective' but also 'highly consequential' as the engine officers viewed it, which constitutes a clear internal contradiction that is reflective of the low-load deterioration debate in academia.

Practical ranking by implementability: experts prioritise what can be executed with minimal disruption.

Low downtime and verification of efficacy were key criteria for short term decision making. Basic voyage and trim optimisation and energy saving through improved crew performance can be achieved and were described as "easy wins" provided a full KPI set is in place. More complex retrofits such as ALS, WHR and PTO/PTI were seen as long term strategic play but were considered hard to implement due to off-hire, limited availability of yards and complexity of integration.

To a number of respondents bunkering quality management (stability/compatibility control, contamination avoidance, sampling and verification) was an effective shipboard Energy Efficiency Measure (EEM) because of its potential to avert operational instability and efficiency losing events such as filter blockages, purifier seizures, unscheduled repairs and performance loss. One or two of the experts also pointed out that the adverse effects of "bad fuel" would be mitigated by other EEMs.

3.2. Biofuels (FAME & HVO)

3.2.1. Literature review (evidence synthesis and measure-level differentiation)

Recently Biofuels have been discussed as a near-term measure to help achieve the decarbonisation of shipping. Although recent literature has started to clarify the need for more specificity, as the term "biofuels" includes substances that are not similar in properties, and therefore not similar in terms of reliability and likelihood of requiring maintenance repairs. For example FAME (fatty acid methyl esters) and HVO (hydrotreated vegetable oil, renewable diesel) have very different physical and chemical properties. Ultimately the question is not whether or not biofuels lead to a reduction of greenhouse gas emissions throughout their lifecycle, but also whether their use is compatible with the reliability of the systems in which they are integrated, their storage capacity, as well as the lifespan of engines.

FAME: On the heels of multiple recent reviews and studies, it's clear that FAMEs are prone to oxidative degradation and quality loss over time and under normal handling and storage conditions. A review of long term storage by Ai et al highlights factors which influence FAME stability including oxygen, temperature, light, moisture, microbes and metal catalysis with an increase in acid value, viscosity and precipitate over time (Ai et al., 2024). lly, the phenomenon of storage instability turns from being a theory to being an operational issue when the by-products of the degradation (acids, gums, insolubles) start to cause problems for filtration and injection. When planning for sea-birth of off-specification fuel, this phenomenon becomes operational too. The impact of water is not negligible as shown by an experiment led by Christensen & McCormick. Indeed water contamination of FAME can lead to oxidation pathways and acids and gums are formed potentially decreasing the lifespan of engines. (Christensen & McCormick, 2023).

One more constraint is microbial contamination. Although microbial contamination is encountered with conventional fuels, microbial contamination in biodiesel blends presents more favorable conditions (water affinity and nutrient availability) to microorganism growth, potentially resulting in clogging, sludge precipitation and microbiologically influenced corrosion (MIC). Recent evidence syntheses confirm microbial contamination and MIC as non-negligible risk factors related to storage of biodiesel blends, as their severity has been associated to the biodiesel content and to storage conditions (Ai et al., 2024).

There is a growing number of technical publications focused on marine engines that clearly distinguish between different biofuel types. In Faitar et al. (2025) the author's contrast the effects of biofuels on marine main engine operations and the reduced maintenance of durability factors. FAME has higher oxygen content and different properties that can result in higher combustion temperature and NOx emissions at low load engine operation and also affect durability-related issues in the engine and its components (Faitar et al., 2025). The implication is that FAME's regulatory appeal may be offset by operational and maintenance externalities if storage duration, climate, and system design are unfavorable conditions typical for deep-sea shipping.

HVO: HVO is generally characterised as a paraffinic, low-aromatic, sulfur-free fuel with high cetane value and stable storage similar to conventional diesel fuel. The most recent papers deal with combustion and emissions. According to the work of Millo et al. HVO, when used as a neat fuel in a highly developed modern diesel engine (without engine calibration) shows strong reduction of pollutants and only a moderate increase of brake specific fuel consumption, under the test conditions considered (Millo et al., 2025). Although not marine-specific, these combustion mechanisms (high cetane, absence of aromatics) are directly relevant to marine distillate applications and consistent with marine-oriented assessments. Study Faitar et al. study also characterizes HVO as a fuel that burns more like a traditional marine diesel, with cleaner combustion and lower particulate emissions than alternative fuel options. The study generally finds lower risk for maintenance durability of the engine with HVO than with alternative biodiesel routes such as FAME (Faitar et al., 2025).

In addition to the lubrication/tribology research related to injection equipment and pumps mentioned above, the HVO boundary behavior was investigated. Kuszewski et al. investigated the lubricity of HVO–diesel blends and the scuffing-load conditions under which they could be injected. They showed that some additive treatment was required to enhance lubricity, but concluded that this is a design variable that can be managed, and is not an uncontrollable chemical reaction, such as the oxidation and microbial attacks of FAMEs. (Kuszewski et al., 2025).

3.2.2. Expert interview results (what operators actually accept, reject, and why)

These interviews showed a clear demarcation between 'biofuels as compliance tools' and 'biofuels as technical alternatives'. Two dominant patterns were identified: i) FAME was characterised as an operationally unstable biofuel; ii) HVO was recognised as an operationally feasible alternative, but is held back by market constraints. The distinction between these patterns was not explained in terms of sustainability, but in terms of specific engineering criteria such as storage, the performance of separators, filters, seals and prevention of deposit formation.

FAME: broad rejection driven by storage and reliability, with limited minority acceptance.

Across chief engineers and technical superintendents, FAME was repeatedly described as a fuel that "forces the ship to adapt to the fuel," rather than the other way around. One chief engineer reported that FAME blends were associated with higher separator load and repeated filter attention interpreted operationally as a stability/contamination symptom consistent with the oxidation-and-water pathways described in the literature. Another technical manager emphasized that even when the fuel arrives "in spec," the ship's tank environment (residual water, temperature variation, long residence time) is structurally incompatible with the assumption of short storage cycles.

That said, there was a minority "conditional acceptance" position voiced by at least one fuel-quality specialist: FAME can be used if storage is tightly managed, turnover is high, and housekeeping is strict (water control, frequent monitoring, conservative blending) and the price is considerably better than HVO. This is a technically coherent position but it is operationally fragile. A senior engineer countered the point directly: deep-sea operations do not reliably permit tight turnover cycles or controlled storage environments, so the "manageable" scenario is not representative of real trading patterns. In short: **the disagreement is not about chemistry, but about operational realism**.

HVO: strong operational acceptance, but constrained by supply and price.

While many engineers mentioned that HVO "acted like a clean diesel" and there were no operational incidents related to storage, microbial contamination or system incompatibilities, this is also in line with expectations based on literature which describes HVO as paraffinic and stable, and based on the aforementioned tests which confirm the possibility to obtain a similar combustion efficiency to conventional diesel. Any concerns are related more to commercial rather than to engineering grounds, including lack of consistency of availability across bunker hubs and higher relative cost compared to traditional distillates.

A regulatory expert with a focus on compliance added a new perspective to our discussions. The expert framed HVO as the biofuel with the lowest risk of not achieving lifecycle compliance goals while still ensuring that the product does not cause operational reliability issues. The expert hence framed HVO as the premium compliance option when budget allows. Several of the technical management respondents agreed that FAME having lower reliability due to its higher variability, which could eliminate a part of the compliance benefit due to more frequent shutdowns and more maintenance work - which can also be seen as an expression of the "hidden costs" we read about in relation to materials-compatibility and storage-stability.

Table 1. Comparative Summary of Energy Efficiency Measures and Biofuels (FAME/HVO)

Category	Effectiveness	Implementation	Operational Risk	Regulatory Value	Expert Consensus
Hull condition management	High (3–8% fuel savings)	High (low downtime; routine operations)	Low (predictable, purely physical mechanisms)	Moderate (improves CII)	Strong support
Propeller retrofits & ESDs	Medium–High (2–7% depending on wake-field match)	Medium (requires docking + hydrodynamic assessment)	Medium (mismatch can negate benefits)	Moderate	Conditional support
Air Lubrication Systems (ALS)	Medium–High (5–10% under stable conditions)	Low (high CAPEX & integration complexity)	Medium–High (sensitive to tuning & sea state)	Moderate	Split views – managers positive, engineers cautious
Waste Heat Recovery (WHR)	Medium (3–6% SFOC reduction)	Low (structural retrofit; space constraints)	Medium (system complexity)	Moderate–High (strong CII/EEXI stabiliser)	Support with reservations – "effective, but painful to install"
Shaft generators (PTO/PTI)	Medium (profile-dependent fuel reduction)	Medium (electrical system integration)	Medium (incorrect load management = no gain)	High (CII/ETS benefit)	Mixed – requires crew competence and system tuning
Predictive maintenance / performance monitoring	High (long-term) (avoids 2–4% efficiency drift)	Medium (requires sensors, analytics)	Low (reduces technical failures)	Indirect (protects CII baseline)	Strong support – viewed as "efficiency stabiliser"
Slow steaming	Very High (theoretical)	High (no retrofit)	High (engine low-load deterioration)	High	Highly divided – managers favour it, engineers warn of damage
Voyage/trim optimisation & EMS	Low–Medium (1–3% depending on profile)	High (software & training)	Low	Moderate	Unanimous support as "easy wins"
FAME	Neutral to Negative (TTW); 35–70%	High (drop-in) but storage-sensitive	Very High – oxidation, water absorption,	High (FuelEU)	Overwhelming rejection for deep-sea; one minority

	WtW GHG reduction		microbial growth, material degradation		"conditional acceptance"
HVO	Neutral TTW; 70–90% WtW GHG reduction	High (drop-in)	Low – stable, non-hygroscopic, diesel-like	Very High	**Strong acceptance** – "the only biofuel we trust"; constrained by price & availability

4. Conclusion

This study indicate that the application of Energy Efficiency Measures (EEMs) and biofuels are good options to reduce emissions from ships but they belong to different dimensions of the work to reduce GHG emissions from ships. The EEMs improve the physical efficiency of the ship while the biofuels reduces the lifecycle intensity of the fuel consumed without reducing the amount of fuel required to operate the vessel. According to the systematic literature review conducted, the most reliable and quantified benefits of EEMs have been achieved by hydrodynamic optimisation, propulsion upgrade and equipment efficiency improvements, achieving fuel savings in the order of 5-20% and therefore enhancing the Carbon Intensity Index (CII) /Energy Efficiency Ex-Ship Index (EEXI) of the vessel. Also, hull and propeller condition management is a cost-effective way to improve the efficiency of ships. Although more complex retrofitting measures such as Waste Heat Recovery (WHR), shaft generators and air-lubrication systems have large potential, they are limited by their high capital expenditure (CAPEX), as well as their complexity in terms of integration and their high sensitivity to operational profiles.

The results of the expert interviews agree with our findings, but they also provide some additional details that are important for a complete understanding. For example, the priority of the engineering community for efficiency measures lies in the direction of automated and therefore highly predictable energy savings as opposed to optimization of power output during low demand periods or reliability operations or measures that heavily depend on human action. Additional important aspects are derived from the comments on the need for quality of fuel and the adequacy of building maintenance practices in order to ensure that efficiency improvements pay-off in the long term.

The article finds that biofuels, notably FAME and HVO, have a large divergence between their regulatory value and their actual operational performance. Based on a survey of literature and from expert testimony, the performance of FAME is limited by causes including oxidation, humidity, microbes and material incompatibilities and thus is not suitable for long sea voyages and harsh conditions of storage. In contrast, HVO can deliver high WtW GHG reductions with diesel similar stability and combustion characteristics and is the only drop-in biofuel where compliance can be achieved without the need for operational concessions. Instead, performance is constrained by current market availability and price conditions.

Based on current data, a prudent approach to decarbonisation of deep-sea shipping would have EEMs at the core of the efficient operations, with HVO being used as a transition fuel to ensure compliance with the regulations. FAME will only have a niche role in very specific and controlled short sea applications and is not a viable alternative as a low carbon fuel for the global tramp and liner segments. Moving forward, the focus should be on monitoring engine and vessel performance in real time, ensuring that fuel systems are robust and that condition-based maintenance and performance forecasting tools are implemented.

Author contributions:

- Conceptualization: A.H. and I.D. (author's name initials)
- Methodology: I.D.
- Investigation: I.D. and A.H.
- Writing original draft: A.H.

- Writing review and editing: I.D.
- Supervision: I.D. and A.H.

Conflict of interest: The Author's declare no Conflict of interest.

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