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Strategies for enhancing the energy efficiency of ships within the framework of global decarbonization

Abstract: The relevance of improving energy efficiency in seagoing vessels is growing due to global decarbonization, stricter environmental standards, and increasing demands to reduce greenhouse gas emissions in the maritime sector. This study aimed to conduct a comprehensive analysis of innovative strategies for improving ship energy efficiency, taking into account current decarbonization trends, as well as to evaluate their impact on the environmental and economic performance of maritime transport. A range of methods, including statistical analysis, empirical approaches, and experimental techniques, was used to study the impact of new technologies. A comparative analysis of three fuel types – diesel, biofuel Romashka-3, and LNG – focused on consumption, emissions, and voyage costs. The results show that biofuel reduces CO_2 emissions by 19% and voyage costs by 6%. LNG

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provides the greatest emission reductions – CO_2 by 20%, NO_x by 49%, and SO_x by 95% – though it increases voyage costs by 6%. Diesel, with the highest emissions and a cost of USD 33.7 thousand, is the most environmentally harmful. The findings suggest that the optimal strategy involves a gradual transition to alternative fuels and digital solutions to improve energy efficiency without major economic trade-offs. This research offers practical value by helping shipping companies, fleet operators, policymakers, and regulators improve energy efficiency, reduce environmental impact, and support fleet modernization and sustainable transport policies.

KEYWORDS: maritime sector, alternative fuel, liquefied natural gas, biofuel, marine engine

Introduction

The issue of enhancing the energy efficiency of the maritime industry has become particularly pressing in the context of global decarbonization and the tightening requirements of international organizations for reducing greenhouse gas emissions. Energy efficiency, in the context of this study, refers to the optimal use of energy resources in maritime operations, aiming to reduce fuel consumption while maintaining or improving the performance and safety of vessels. This involves adopting technological innovations, alternative fuels, and operational strategies that lower energy use without compromising service quality. Decarbonization, on the other hand, refers to the process of reducing carbon dioxide (CO_2) emissions from maritime activities, primarily by transitioning to low-carbon technologies, alternative fuels, and enhancing energy efficiency. The perspective adopted in this study focuses on evaluating the impact of various strategies, including the use of alternative fuels and digital optimization, on improving energy efficiency while supporting the decarbonization goals of the maritime industry in line with international environmental standards.

The work of Veshapidze et al. (2024) demonstrated that energy decarbonization is a key prerequisite for the sustainable development of Georgia, proving that national strategies for transitioning to low-carbon technologies have a direct impact on the transport sector, particularly enhancing overall energy efficiency and reducing greenhouse gas emissions. Georgia's strategic position, its commitment to meeting international environmental standards, and the challenges it faces in adapting to global decarbonization trends make it a valuable case for understanding how national efforts can align with global sustainability goals. Studying Georgia provides insights into the broader implications of decarbonization for emerging economies and transport sectors in transition. Janjghava et al. (2025) revealed the potential of implementing "cold ironing" technology in Georgian ports, which significantly reduces emissions while ships are berthed, providing a cleaner alternative during port stays. Vadachkoria et al. (2025) assessed the influence of training programs on the environmental awareness of future seafarers using the example of the Batumi Maritime Training Centre, highlighting an increase in the adoption of green practices among maritime professionals. Díaz-Secades (2024) demonstrated the effectiveness of integrating fishing vessels into the International Maritime Organization energy efficiency standards, significantly reducing the carbon footprint in this segment, while also improving fuel consumption patterns and operational costs in the long run.

In the publication by Nisiforou et al. (2022), a roadmap for decarbonizing shipping in Cyprus was proposed, involving stakeholders and demonstrating that public and business engagement can drive effective solutions, fostering a collaborative approach to reducing emissions in the shipping sector. The authors also highlighted the potential for policy frameworks to stimulate sustainable practices. Brown et al. (2024) examined the response of climate policies to changes in the political paradigm in the United States and the state of Georgia, emphasizing the interdependence between the political context and the effectiveness of decarbonization programs. They found that political shifts could either accelerate or hinder the implementation of green policies. Grzelakowski et al. (2022) proposed a roadmap towards achieving zero emissions in maritime shipping as part of global supply chains, identifying regulatory and economic conditions critical for this transition. They demonstrated that achieving zero emissions is possible within the existing global supply chains through a combination of regulatory changes, technological advancements, and market-driven incentives, although further experiments on fuel and engine technologies are needed to implement these solutions effectively.

Vakili et al. (2022) presented an interdisciplinary model for overcoming barriers to energy efficiency improvement, using the example of an Iranian shipping company, and emphasized organizational challenges while highlighting the importance of internal adjustments for improving energy performance. Tu et al. (2024) examined the economic feasibility of alternative fuels and energy efficiency measures in the decarbonization process, demonstrating considerable potential for cost and emission reductions. Wang et al. (2022) systematized methods for enhancing ship energy efficiency, including technical and organizational solutions, offering valuable insights into potential strategies for reducing emissions.

An analysis of scientific sources has shown that the improvement of ship energy efficiency directly depends on the characteristics of the technologies employed – the type of power units, the fuel used, the level of digital integration, and management systems. Key factors include the ability of engines to ensure stable performance with reduced fuel consumption, to minimize CO_2 emissions, and to maintain efficiency throughout the vessel's operational cycle (Babak et al. 2005; Golub et al. 2018; Red'ko et al. 2019). At the same time, the combined impact of ship engine modernization, the use of alternative fuels, and digital management systems on energy efficiency and decarbonization in maritime transport remains insufficiently studied.

The existing studies on decarbonizing maritime transport reveal several key gaps. Many works focused on organizational challenges and stakeholder engagement, but did not explore the technical aspects of implementing alternative fuels or the practical testing of fuel systems. While some studies demonstrated the potential for emission reductions and cost savings, they primarily relied on modeling approaches without empirical verification or real-world data from actual vessels. Additionally, although the importance of regulatory frameworks and the economic feasibility of alternative fuels was acknowledged, there was insufficient attention to testing innovative power plants or next-generation biofuels, which are critical for addressing modern climate challenges. Furthermore, while some studies proposed comprehensive roadmaps for achieving zero emissions, they lacked practical experimentation on fuel or engine technologies that would support the proposed strategies.

The main objective of this research was to examine innovative strategies for enhancing energy efficiency in shipping in the context of decarbonization processes, and to determine their impact on the sustainable operation of maritime transport from both environmental and economic perspectives. The research tasks included: a comparative analysis of fuel consumption, pollution levels, and voyage costs based on different shipping solutions; the assessment of the potential for transitioning to alternative fuels; and the generalization of results in the form of an integrated index of maritime transport energy efficiency.

1. Materials and methods

1.1. Sample description

The objects of analysis in this study were five ships of different types, operating regular voyages in the Black Sea basin. To ensure confidentiality, the data were anonymized, and the vessels were designated as "Ship 1-5". The sample was formed according to several inclusion criteria: the presence of modern monitoring systems, technical suitability for the installation of additional measuring devices, regular voyages during the study period, and the absence of major modernization during the experiment that could distort the results. The sample included ships of different categories – bulk carriers, container ships, tankers, passenger vessels, and general cargo – which allowed for the collection of representative data and consideration of various operational features. Ships undergoing prolonged repair, not performing regular voyages, or with incomplete measurement data were excluded. This approach enabled the formation of a sample both sufficient for statistically reliable conclusions and balanced across ship types.

1.2. Equipment and data collection

Empirical data collection was carried out using FlowTech FT-200 (Germany) specialized sensors, integrated into the fuel and exhaust systems. The sensors ensured continuous monitoring of the following indicators: fuel consumption (l/h), CO_2, NO_x, and SO_x emissions (g/km), voyage duration, route length (km), vessel speed, average engine load, as well as voyage cost, calculated based on actual fuel consumption and its price. The obtained data were stored in Comma-Separated Values format, which allowed for subsequent computer processing. High-resolution sensor data enabled fuel impact modeling.

1.3. Experimental design

The data collected from the sensors were initially processed in Microsoft Excel, where tables, graphs, and fundamental statistical indicators were generated. For more in-depth analysis, IBM SPSS Statistics (version 27) was applied, which enabled correlation, regression, and factor analysis. This approach helped determine relationships between various parameters, including fuel consumption, voyage length, vessel type, emission volumes, and overall voyage costs.

Another stage of the research involved studying the impact of different fuels on energy efficiency and environmental performance. For this purpose, a MAN B&W 6S50ME-C9.6 (Denmark) test engine was used – a modern two-stroke, low-speed diesel unit widely employed in global merchant fleets. The choice of this engine was determined by its widespread use in shipping and its capacity for adaptation to different fuel types. A series of tests was conducted on the engine using both conventional and alternative fuels. The comparison included three primary fuels: diesel fuel of grade DMB ISO 8217:2017, serving as the baseline option; Romashka-3 biofuel, developed from a blend of rapeseed oil, fatty acid methyl esters, and ethanol additives; and liquefied natural gas (LNG), positioned as a low-carbon fuel with prospects for broad adoption. Inclusion criteria were certification, compliance with International Maritime Organization international standards, and technical compatibility with the engine under study. Fuels lacking certification or causing combustion instability were excluded. The comparative analysis of test results was based on key indicators: fuel consumption per voyage kilometer, levels of CO_2, NO_x, and SO_x emissions, cost of fuel used per voyage, and potential savings (or overspend) when switching from diesel to alternative fuels. The comparative analysis enabled the alignment of actual sensor data with the results of test-bench experiments, and the evaluation of economic and environmental benefits that could be achieved by switching to new fuels.

1.4. Statistical analysis

The application of a combination of statistical and comparative methods ensured the comprehensiveness of the research. Initially, real voyage data from five vessels were collected and statistically processed, allowing for the determination of baseline energy efficiency and environmental pollution indicators. These data were then compared with modeling results on the test engine, enabling the calculation of differences between actual expenditures and potential outcomes if alternative fuels were applied. This approach provided an objective assessment of the impact of innovative solutions on maritime transport within the context of global decarbonization. The final stage involved integrating the results into a generalization system, which included the formation of an integrated index of shipping energy efficiency (1):

$$I = \sum_{i=1}^{n} wi \cdot xi \tag{1}$$

where:

- xi – normalized values of individual indicators (fuel consumption, CO_2, NO_x, SO_x emissions, voyage cost);
- wi – weighting coefficients reflecting the relative significance of each indicator in the overall index,
- n – the number of indicators included in the calculation.

This index considered the relationship between fuel costs, emission levels, and voyage costs, allowing for a comparison of the efficiency of different strategies. Such a system provided the basis for subsequent recommendations aimed at optimizing ship energy consumption, developing the biofuel sector, and introducing digital management systems.

2. Results

2.1. Operational performance analysis

Field measurements on five vessels undertaking regular voyages in the Black Sea basin provided a detailed picture of their actual energy use and environmental impact. Voyage costs were determined by route length, the level of fuel consumption, and the average market price of fuel during the study period. It was found that short routes did not yield the expected savings: for example, a 200 km voyage by Ship 1 proved comparable in cost to medium-length voyages of 350–500 km. On a normalized cost scale, Ship 1 received the highest scores, confirming its low economic efficiency under current conditions. The measurement results are summarized in Table 1, enabling a comparison of key operational indicators.

Table 1. Key operational indicators for five vessels (field measurement results)

Tabela 1. Kluczowe wskaźniki operacyjne dla pięciu jednostek (wyniki pomiarów terenowych)

Vessel	Voyage length [km]	Fuel type	Fuel consumption (1–10)	Pollution level (1–10)	Voyage cost (1–10)
Ship 1	200	Diesel (grade 234)	10/10	4/10	10/10
Ship 2	350	Diesel (grade 234)	9/10	5/10	9/10
Ship 3	500	Diesel (grade 234)	8/10	6/10	8/10
Ship 4	650	Diesel (grade 234)	7/10	7/10	7/10
Ship 5	800	Diesel (grade 234)	6/10	8/10	6/10

Source: created by the authors based on FlowTech FT-200 sensor data (Germany).

As Table 1 shows, there is a clear trend: as voyage length increases, relative fuel consumption decreases (in terms of the normalized scale), yet atmospheric pollution levels and the overall financial cost per voyage rise. This means diesel engines operate more efficiently over longer distances in terms of fuel per kilometer, but the total environmental and economic burden becomes higher. The analysis of the five ships highlights how voyage length influences fuel consumption, emissions, and costs. Shorter voyages, like Ship 1's 200 km trip, show high fuel consumption and economic inefficiency, but relatively low emissions due to the brief duration. As the voyage length increases, fuel consumption per kilometer improves, but both emissions and costs rise. Medium-length voyages, such as those of Ships 2 and 3, provide a better balance, with moderate fuel use and emissions, showing more stability in operational costs and environmental impact. Longer voyages, like those of Ships 4 and 5, result in lower fuel consumption per kilometer but higher overall emissions and costs. Ship 5 exhibited the highest total emission load, despite lower per-kilometer fuel consumption. This analysis demonstrates that medium-length voyages tend to offer the most optimal trade-off between fuel efficiency and emissions, while longer routes, though more fuel-efficient, incur greater environmental costs.

These results illustrate a complex balance between the economic and environmental parameters of voyages. Short routes yield lower total emissions but have high costs and inefficient fuel use; long routes are more economical per kilometer but markedly increase the aggregate volume of harmful emissions. Medium routes (350–500 km) proved the most optimal in terms of the cost-pollution trade-off, where vessels demonstrated balanced outcomes.

2.2. Alternative fuel comparison and emission reduction potential

The field data from the five test vessels served as a starting point for modeling alternative fuel-use scenarios. The comparison of three fuels was carried out against key criteria, including fuel consumption (tonnes per voyage), CO_2, NO_x, and SO_x emission levels (in relative and absolute terms), voyage cost in US dollars, and the potential saving or overspend relative to the baseline diesel scenario. To illustrate applied results, indicators for Ship 1 were analyzed; these are presented in Table 2.

Analysis of the results in Table 2 shows that switching to the "Romashka-3" biofuel reduced CO_2 emissions by 19% and voyage costs by 6%. Compared with the diesel baseline, LNG reduced CO_2 by 20%, NO_x by 49%, and SO_x by 95%, but increased voyage costs by 6%. This confirms the different nature of the advantages: biofuel optimizes the balance between economy and ecology, whereas LNG provides the maximum environmental effect at somewhat higher cost. Subsequent analysis covered all five vessels, revealing general regularities. Figure 1 shows the change in CO_2 emissions when switching from diesel to biofuel and LNG.

Figure 1 demonstrates that for all five vessels, CO_2 emissions decrease when switching to both biofuel and LNG. The indicators are relatively consistent: "Romashka-3" biofuel delivers reductions in the range of 18–19%, while LNG achieves a slightly better result –

Table 2. Comparison of indicators for Ship 1 across three fuels

Tabela 2. Porównanie wskaźników dla Statku 1 przy trzech rodzajach paliwa

Indicator	Diesel (DMB)	Biofuel "Romashka-3"	LNG
Fuel consumption [t]	110	115	98
CO_2 emissions [t]	345	280 (–19%)	275 (–20%)
NO_x emissions [kg]	410	300 (–27%)	210 (–49%)
SO_x emissions [kg]	95	40 (–58%)	5 (–95%)
Voyage cost [USD]	32,800	30,900 (–6%)	34,650 (+6%)

Source: created by the authors based on test-bench trials.

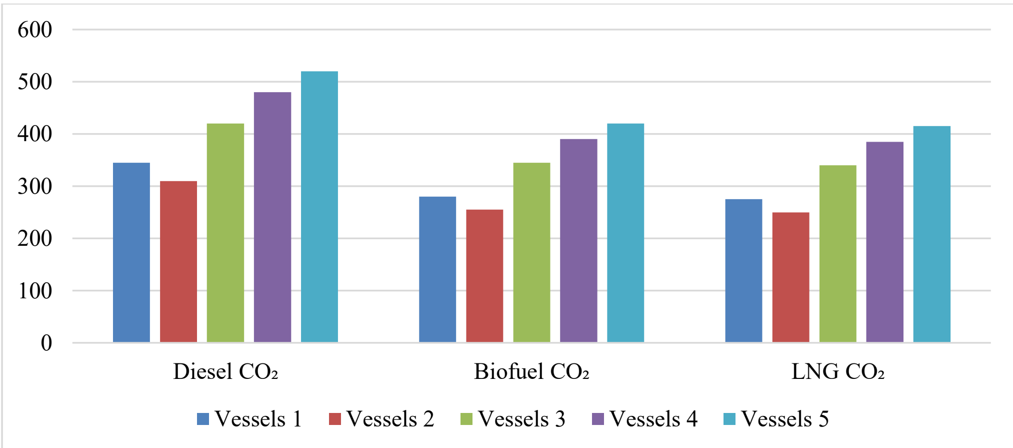

Fig. 1. Change in CO_2 emissions when switching from diesel to biofuel and LNG
Source: created by the authors based on test-bench trials

Rys. 1. Zmiana emisji CO_2 przy przejściu z oleju napędowego na biopaliwo i LNG

approximately 20%. The difference between the two alternatives in CO_2 reduction generally does not exceed 2–3%; however, with LNG, there is an additional, substantial decrease in other harmful substances: nitrogen oxides (NO_x) by almost half and sulphur oxides (SO_x) by more than 90%. This indicates that LNG has greater environmental potential and can be considered a strategically safer option for the future development of shipping, especially in the context of stricter International Maritime Organization standards (2023). At the same time, biofuel – despite a slightly smaller environmental effect – has the advantage of availability and does not require such an extensive infrastructure overhaul, making it more realistic for rapid deployment (Panchenko et al. 2021; Voloshina et al. 2021). Figure 2 shows the change in voyage cost by fuel type and enables an assessment of the economic feasibility of switching from diesel to alternative energy sources.

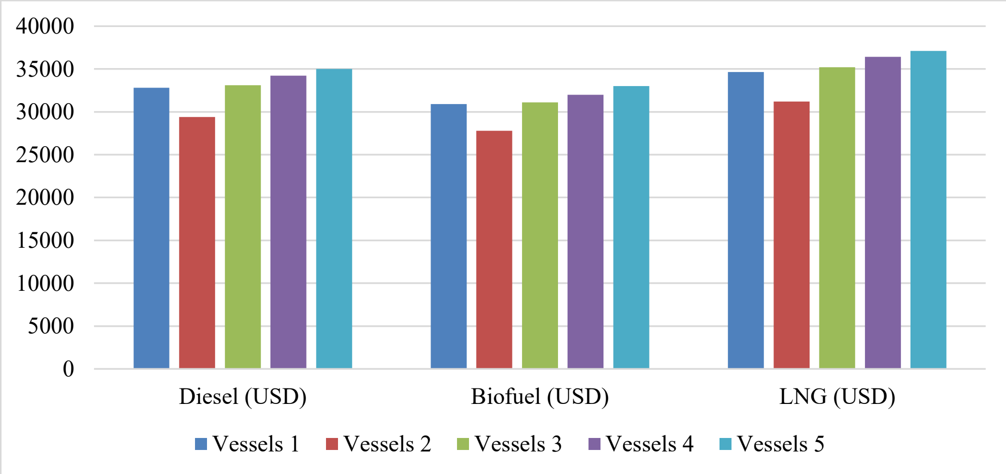

Fig. 2. Change in voyage cost under different fuels
Source: created by the authors based on test-bench trials

Rys. 2. Zmiana kosztów rejsu przy różnych rodzajach paliwa

As Figure 2 shows, biofuel yields an average saving of USD 1.5–2 thousand per voyage compared with diesel, whereas LNG, conversely, increases costs by USD 1.8–2.1 thousand. This confirms that biofuel can be a viable compromise solution for companies seeking to reduce their environmental footprint while optimizing financial performance.

The comparative analysis enabled a quantitative assessment of the practical effectiveness of different fuels. It was established that average diesel consumption for the five test vessels was 388 t per voyage, with corresponding CO_2 emissions of 415 t and an average voyage cost of about USD 33.7 thousand. Switching to "Romashka-3" biofuel reduced average CO_2 emissions to 338 t (–18%), cut SO_x by 58%, and lowered costs to USD 30.9 thousand (–6%), despite a slightly higher volume of fuel consumed. LNG, in turn, showed the lowest emissions – 333 t CO_2 (–20%), almost half the NO_x, and more than a 90% reduction in SO_x – yet average voyage costs rose to USD 34.9 thousand (+6%). The aggregated results of the integrated energy-efficiency index (per formula 1) corroborated these trends: for diesel, the index was 0.82, reflecting its environmental harm and strategic unprofitability; for "Romashka-3" biofuel, it fell to 0.63 owing to the combination of ecological effect and economic benefit; for LNG the lowest value – 0.58 – was obtained, indicating the highest environmental efficiency, albeit with higher costs.

2.3. Fuel comparison, energy efficiency index, and strategic recommendations

The findings show that no single fuel can be regarded as a universal solution: each has its own advantages and constraints. Diesel remains the most accessible option due to its established infrastructure, yet it exhibits the highest CO_2, NO_x, and SO_x emissions, making it strategically disadvantageous amid tightening environmental regulations. LNG proved the most environmentally effective – the reduction in CO_2 reaches one-fifth, and sulphur oxide emissions are almost eliminated. This directly aligns with International Maritime Organization requirements (2023) and allows LNG to be considered a promising option in a medium-term decarbonization strategy. However, its use is accompanied by higher costs and requires the development of specialized port infrastructure, including storage and bunkering systems. The "Romashka-3" biofuel occupies an intermediate position between economic viability and environmental effect. It provides CO_2 reductions and lower voyage costs, making it a more balanced option for the transition period. The main challenge remains the lack of a developed biofuel production and logistics system, which requires additional investment and international certification (Akbarov et al. 2024; Kryvoruchko et al. 2021). Thus, LNG may be viewed as the most promising fuel environmentally; "Romashka-3" biofuel as a compromise that combines economic benefits with partial environmental gains; while diesel is progressively losing its rationale due to high emissions and anticipated regulatory constraints. The results lay the groundwork for a multi-layered energy-efficiency strategy in shipping that combines the adoption of alternative fuels with digital solutions and the development of "green" port corridors.

A distinct strategic direction should be the deployment of digital voyage optimization technologies. As the field results showed, even when using the same fuel, digital route optimization and operational automation (including berthing and engine load distribution) can reduce fuel consumption by 5–10% and cut CO_2 emissions by a similar proportion. Digitalization can therefore be regarded as a universal tool that amplifies the effectiveness of any fuel strategy. It requires less capital investment than power plant modernization but delivers rapid, measurable effects. To summarize the recommendations, the results are presented in Table 3.

Table 3 presents a comparison of different strategies for improving energy efficiency, outlining the environmental effects, economic implications, and challenges associated with each. LNG emerges as the most effective in reducing harmful emissions, achieving a 20–25% reduction in CO_2, a 50% reduction in NO_x, and a 95% reduction in SO_x. The higher cost of LNG and the need for new infrastructure result in a 5–7% increase in voyage costs. In contrast, the biofuel "Romashka-3" offers a more balanced profile, reducing CO_2 by 15–20%, NO_x by 25%, and SO_x by 58%, while also lowering voyage costs by 5–6%. However, its widespread adoption is limited by production constraints and the need for international certification. Diesel remains the least costly in the short term due to established infrastructure and lower fuel prices, but it results in the highest emissions and is increasingly disadvantaged as global environmental regulations tighten (Adamchuk et al. 2016; Marignetti et al. 2020b). Digital voyage optimization, although

Table 3. Recommended scenarios for improving energy efficiency

Tabela 3. Zalecane scenariusze poprawy efektywności energetycznej

Strategy	Environmental effect	Economic effect	Constraints/challenges
LNG	–20–25% CO_2, –50% NO_x, –95% SO_x	+5–7% to voyage cost	High capital expenditure; need for new infrastructure
Biofuel “Romashka-3”	–15–20% CO_2, –25% NO_x, –58% SO_x	–5–6% voyage cost	Limited production; need for certification
Diesel	Baseline (highest emissions)	Lowest price in the short term	Strategically loss-making; high emissions
Digital voyage optimization	–5–10% CO_2 (additional to any fuel)	–3–5% voyage cost	Need to implement digital systems and train personnel

Source: created by the authors based on field and test-bench studies

not directly tied to fuel type, can further reduce CO_2 emissions by 5–10% and decrease transport costs by 3–5%, although its implementation requires investments in digital systems and staff training. This highlights the varying trade-offs between cost, emissions reduction, and the need for infrastructure development across the different strategies.

In summary, an energy-efficiency strategy in shipping should be based on a multi-level approach combining a set of short-, medium-, and long-term measures. In the short term, the most effective strategy involves implementing digital voyage optimization and gradually transitioning to biofuels, which can reduce both operational costs and emissions without the need for substantial infrastructure investment. In the medium term, the focus should be on developing the infrastructure required for LNG, including the establishment of terminals and supply systems, which would lead to significant reductions in emissions as LNG becomes integrated into international shipping routes. In the long term, the goal should be to create a network of fully “green” ports that support alternative fuels, incorporate renewable energy sources, and deploy advanced energy-management systems. This phased approach allows for a gradual, systemic transformation of maritime transport, aligning with international environmental standards while optimizing fuel efficiency and reducing emissions.

3. Discussion

The results obtained confirmed that the transition of maritime transport to alternative fuels is a decisive factor in reducing the carbon footprint and improving fleet energy efficiency. In particular, the test-bench trials demonstrated that LNG provides the most significant environmental effect, while the biofuel “Romashka-3” shows a balanced relationship between economic and ecological parameters.

The real environmental impact of ship emissions requires more detailed analysis that goes beyond simply measuring direct CO_2, NO_x, and SO_x emissions. The impact on air quality, particularly on levels of particulate matter (PM) and black carbon, as well as the impact of secondary pollutants such as ozone and sulfur aerosols, must be taken into account (Marignetti and Rubino, 2023; Sevdimaliyev et al. 2023). These pollutants have a significant impact on human health, particularly in port areas where maritime transport is a major source of pollution. Although the transition to LNG and Romashka-3 biofuel demonstrates a reduction in direct emissions of CO_2, NO_x, and SO_x, it may also lead to a reduction in the formation of harmful secondary pollutants. In particular, a 95% reduction in SO_x when using LNG could significantly reduce the concentration of sulfur aerosols, contributing to improved air quality and reduced health risks.

At the same time, the assessment of the environmental benefits of alternative fuels should include not only direct emissions, but also the entire fuel life cycle – from production to transportation and storage. This will allow for a more accurate assessment of the true environmental impact, as additional emissions of CO_2 and other pollutants during production can reduce the effectiveness of environmental benefits (Pstrowska et al. 2024). Therefore, to fully understand the environmental benefits of alternative fuels, additional research is needed, including monitoring air quality in port areas and assessing the impact on health and ecosystems.

These findings align with the results of Bayraktar et al. (2025), who, through scientometric analysis, demonstrated that the most significant indicators in the maritime sector are energy efficiency metrics directly related to the implementation of digital monitoring technologies and the use of alternative fuels. This is consistent with the results obtained, where FlowTech FT-200 sensors were used to record the relationship between voyage length, specific fuel consumption, and overall pollution volumes.

Similarly, Issa-Zadeh and Garay-Rondero (2025) emphasized that the integration of alternative solutions in port infrastructure opens up the prospects for systematic emission reductions. Notably, the work of Baştuğ et al. (2024), which developed a financial model to support decarbonization initiatives in non-EU countries, aligns with this conclusion. The data presented in their study confirm that LNG is effective from an environmental perspective, but requires substantial investment in new infrastructure and financial mechanisms to support it. This finding is also in line with the study by Kaiser and Chowdhury (2025), which highlighted the potential of hydrogen technologies for shipping, while also pointing out the significant challenges associated with their implementation. Similar trends were described by Shi et al. (2023), who explored the possibilities of using green hydrogen, ammonia, and methanol as fuels for marine engines. On the other hand, Avaritsioti (2025) proved that the business strategies of shipowners are directly dependent on the availability of credit instruments and insurance schemes aimed at "green" technologies. While these options were not experimentally analyzed in this study, the results from the "Romashka-3" biofuel test-bench trials confirm the feasibility of gradually expanding the range of alternative energy sources.

Shafie et al. (2025) provide a comprehensive analysis of hydrogen-rich fuels in decarbonized container ships, addressing the technical, environmental, and economic implications of their adoption. The authors demonstrate the significant potential of hydrogen-rich fuel in reducing greenhouse gas emissions while enhancing the energy efficiency of container vessels. Their work emphasizes the need for a holistic approach to fuel transition, integrating both technological innovation and economic considerations. This study is particularly valuable in understanding the broader framework for implementing low-carbon fuels in maritime transport, which aligns with the current push towards decarbonization within international maritime regulations, such as the IMO's 2050 goals.

Fan et al. (2025) focus on fuel consumption prediction under complex navigating conditions, offering a novel grey box model. This model is essential for accurately forecasting fuel usage across various operational conditions, providing a more nuanced understanding of fuel consumption patterns. The study highlights the complexity of predicting fuel efficiency due to the variable nature of maritime operations, influenced by factors such as weather, vessel speed, and cargo load.

Zhang et al. (2024) take a step further by employing deep learning methods to predict ship fuel consumption in real operational conditions. This approach represents a cutting-edge method of integrating artificial intelligence (AI) with maritime fuel management, offering a more precise and dynamic understanding of fuel usage. By leveraging real-time data and AI algorithms, this research can help shipping companies optimize fuel efficiency on a voyage-by-voyage basis, leading to substantial emissions reductions. The application of deep learning techniques in maritime fuel prediction provides a pathway for more intelligent and adaptive fuel consumption strategies, aligning with the increasing reliance on digital technologies to drive sustainable practices across industries (Akbarova et al. 2024; Aliyev et al. 2024).

The findings from this research emphasize the significant potential of digital technologies, particularly digital voyage optimization, in reducing fuel consumption and CO_2 emissions. This aligns with the work of Aktas et al. (2023) and Virkovska et al. (2023), which highlighted the role of digitalization and intelligent management systems in enhancing operational efficiency. Based on our results, it is evident that the integration of such digital tools should be prioritized in policy, as they provide a cost-effective way to reduce emissions without requiring large-scale infrastructure changes.

The study's findings highlight the critical need for a coordinated approach to infrastructure development, particularly concerning biofuels and LNG. Without the development of these alternative fuel systems, policies such as carbon taxes or trade quotas could impose significant financial burdens on operators, as noted by Psaraftis et al. (2021). In this context, the concept of "green corridors" emerges as a key policy recommendation. By integrating sustainable shipping and port infrastructure, green corridors can facilitate the transition to low-carbon shipping practices. This would not only improve environmental performance but also ensure that financial burdens are minimized by providing the necessary infrastructure for alternative fuels (Marignetti et al. 2020a; Rubino et al. 2018).

A key aspect for reducing emissions is also the development of port infrastructure. Barberi et al. (2021) emphasized in their systematic review that comprehensive emission reductions are only possible if energy-efficient solutions are integrated into ports, reinforcing the importance of developing "green" corridors. These corridors can streamline the adoption of alternative fuels, providing a more efficient and environmentally friendly logistics system. Thus, the promotion of digitalization, coupled with the creation of green corridors, should be integral components of policy strategies aimed at decarbonizing maritime transport.

Additional prospects in this direction were opened by the work of Klakeel et al. (2024), who systematized mature emission reduction technologies that could serve as the basis for further practical integration. The study by Stathatou et al. (2022), which tested biofuel on a bulk carrier, confirmed that the use of biodiesel significantly reduces CO_2 emissions, but real efficiency figures depend on operating conditions. This corresponds with the results obtained, where "Romashka-3" showed a reduction in CO_2 by approximately 18% while simultaneously reducing voyage costs by 5–6%.

The results confirm the need for a systematic approach that combines technical, organizational, and regulatory decarbonization tools. In particular, Karountzos et al. (2023) highlight the importance of geoinformatic solutions for achieving zero emissions in coastal shipping networks. This aligns with the experimental data, where digital route optimization demonstrated an additional reduction in CO_2 by 5–10%, making the integration of information systems a crucial element of the overall strategy. Fu et al. (2025) emphasize the role of emission trading policy in selecting the optimal strategy for a liner fleet. The economic effect observed during the transition to "Romashka-3" biofuel aligns with the authors' conclusions: even a relatively small reduction in voyage costs (–5–6%) could be a critical factor if a carbon tax or quotas are implemented. Similar results were obtained by Melnyk et al. (2025), Shabib et al. (2025), who, in their review, highlighted the lack of practical integration of technologies in ports as the main barrier to sustainability. In this context, the data on the need for LNG and biofuel infrastructure development fully correspond with the identified issues. The regulatory aspect is reflected in the work of Ghoneim et al. (2023), who demonstrated that achieving International Maritime Organization emission goals directly depends on the effectiveness of the regulatory environment. The integrated energy efficiency index established in the study (0.58 for LNG, 0.63 for biofuel, 0.82 for diesel) serves as a practical tool that could be adapted into the monitoring and reporting system according to International Maritime Organization requirements.

Wang et al. (2023) applied the GA-LSTM algorithm to predict vessel energy consumption, proving the effectiveness of big data analysis to improve the accuracy of emissions estimation. This directly corresponds with the use of FlowTech FT-200 sensors, which helped to form an empirical data set for further scenario calculations. Zhou et al. (2025) showed that dual-fuel solutions for tankers result in a significant reduction in emissions based on the Energy Efficiency Design Index, which resonates with the data obtained regarding the advantages of LNG in reducing NO_x and SO_x. In a broader review, Alamoush (2024) and Rud and Rud (2025) addressed the problem of the repetitiveness of decarbonization studies in ports, stressing the need for unified methodologies. The integrated approach combining vessel data analysis, test-bench trials, and economic models can be considered an example of such systematization. New decarbonization trends are closely linked with the use of renewable energy sources. Balaji and You (2024) demonstrated the potential of producing green hydrogen via offshore wind power for supplying coastal shipping routes.

Although these technologies were not included in the presented results, they could become the next step in transforming the fuel balance. Similarly, Evingür and Osma (2025) examined the prospects of integrating solar photovoltaic systems into maritime infrastructure, aligning with the trend of creating "green" ports, consistent with the concept of green corridors.

The results confirm that the implementation of alternative fuels and digital management technologies in the operation of marine vessels not only reduces harmful emissions but also optimizes economic costs per voyage in the medium- and long-term. In the context of previous studies that analyzed the possibilities of biofuels, LNG, and hydrogen solutions, the data obtained align with the conclusions about the need for a multi-level approach to modernizing maritime transport. Specifically, the observed effects of CO_2 reduction by 15–25%, substantial reductions in NO_x and SO_x, stability in voyage costs when using biofuels, and increased efficiency through digital optimization of routes and energy consumption indicate the feasibility of gradually transitioning to mixed strategies. These findings complement the contemporary concept of decarbonizing maritime transport, which involves not only choosing new fuels but also developing infrastructure, digital control systems, and "green" port corridors. The integrated approach developed aligns with leading sustainable shipping concepts. It confirms that the impact of innovative fuels and digital solutions on energy efficiency is systematically determining, both from the technical and economic efficiency perspectives, as well as in terms of meeting international environmental standards and the requirements of global decarbonization.

Conclusions

This study conducted a comprehensive assessment of the impact of different fuel types and energy efficiency strategies on the performance of marine vessels in the context of global decarbonization. The results of field measurements confirmed that diesel fuel provides relative availability and infrastructure, but is accompanied by high levels of CO_2 (an average of 415 t per voyage), NO_x, and SO_x, as well as significant financial burdens (about USD 33,700 per voyage). Short voyages demonstrated the highest cost per kilometer, while long voyages had the most critical total emissions, confirming the strategic inefficiency of diesel fleets in the long term. Test-bench trials showed that "Romashka-3" biofuel reduced CO_2 emissions by 19%, NO_x by 27%, and SO_x by 58%, while lowering voyage costs by 6% compared to the diesel scenario. LNG demonstrated the most significant environmental effect: CO_2 emissions were reduced by 20%, NO_x by almost half (–49%), and SO_x by 95%, although voyage costs rose by 6%.

Thus, LNG is the most promising from an environmental perspective, while biofuel represents a compromise option that combines emission reductions with economic benefits. The calculation of the integrated energy efficiency index confirmed the conclusions: diesel fuel received the lowest result (0.82), "Romashka-3" biofuel showed a medium level (0.63), while LNG demonstrated the highest level of environmental efficiency (0.58), despite increased financial costs. It was additionally established that digital route optimization can reduce fuel consumption and CO_2 emissions by 5–10%, and decrease costs by 3–5%, regardless of the fuel type used.

LNG emerges as the most environmentally effective option, while biofuel offers a balanced approach, reducing emissions while providing economic benefits. The integrated energy efficiency index confirms LNG's superiority in environmental efficiency, despite higher costs, and highlights the potential of digital route optimization to further reduce emissions and costs. The study emphasizes that no single strategy can achieve decarbonization in shipping; a combination of biofuels, LNG, and digital technologies is key for meeting global decarbonization goals.

It is important to note that the sample in this study, which included five ships of different categories – bulk carriers, container ships, tankers, passenger vessels, and general cargo – cannot statistically represent the full diversity of the Black Sea fleet. While the selected vessels provided valuable insights into the operational features and energy efficiency of different ship types, the limited sample size restricts the generalizability of the findings to the entire fleet. This limitation should be taken into account when interpreting the results, and future studies with a larger and more diverse sample of ships are recommended to provide a more comprehensive analysis of energy efficiency and decarbonization strategies across the Black Sea maritime sector.

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References

Adamchuk et al. 2016 – Adamchuk, V., Bulgakov, V., Nadykto, V., Ihnatiev, Y. and Olt, J. 2016. Theoretical research into the power and energy performance of agricultural tractors. *Agronomy Research* 14(5), pp. 1511–1518.

Akbarov et al. 2024 – Akbarov, S.D., Imamaliyeva, J.N. and Akbarli, R.S. 2024. The influence of the fluid flow velocity and direction on the wave dispersion in the initially inhomogeneously stressed hollow cylinder containing this fluid. *Coupled Systems Mechanics* 13(3), pp. 247–275, https://doi.org/10.12989/csm.2024.13.3.247.

Akbarova et al. 2024 – Akbarova, S., Akbarli, R. and Namazov, Y. 2024. Trends in scientific research on technological aspects of green energy transition. *Reliability Theory and Applications* 19 (Special issue 6), pp. 1633–1641, https://doi.org/10.24412/1932-2321-2024-681-1633-1641.

Akhavan, M. 2025. Decarbonising maritime transport: The role of green shipping corridors in making sustainable port-city ecosystems. *Ocean and Society* 2, https://doi.org/10.17645/oas.9411.

Aktas et al. 2023 – Aktas, T.U., Shi, J., Lim, G.J., Prousalidis, J., D'Agostino, F. and Liang, C. 2023. Decarbonization of the Maritime Transportation Systems: Recent progress, challenges, and prospects. [In:] *Proceedings of the Electric Ship Technologies Symposium,* pp. 224–230. Alexandria: IEEE, https://doi.org/10.1109/ESTS56571.2023.10220507.

Alamoush, A.S. 2024. Trends in port decarbonisation research: Are we reinventing the wheel? *Current Opinion in Environmental Sustainability* 71, https://doi.org/10.1016/j.cosust.2024.101478.

Aliyev et al. 2024 – Aliyev, S., Hasanov, R.I., Aghayeva, K., Gasimov, J.Y. and Ahmadova, S.E. 2024. The Relationship between Renewable Energy Consumption and Economic Growth: Insights from Iceland and Azerbaijan. *International Journal of Energy Economics and Policy* 14(5), pp. 229–235, https://doi.org/10.32479/ijeep.16490.

Avaritsioti, E.I. 2025. Shipping decarbonisation: Financial and business strategies for UK shipowners. *Journal of Risk and Financial Management* 18(7), https://doi.org/10.3390/jrfm18070391.

Babak et al. 2005 – Babak, V., Filonenko, S. and Kalita, V. 2005. Acoustic emission under temperature tests of materials. *Aviation* 9(4), pp. 24–28, https://doi.org/10.1080/16487788.2005.9635914.

Balaji, R.K. and You, F. 2024. Sailing towards sustainability: Offshore wind's green hydrogen potential for decarbonization in coastal USA. *Energy & Environmental Science* 17(17), pp. 6138–6156, https://doi.org/10.1039/D4EE01460J.

Barberi et al. 2021 – Barberi, S., Sambito, M., Neduzha, L. and Severino, A. 2021. Pollutant emissions in ports: A comprehensive review. *Infrastructures* 6(8), https://doi.org/10.3390/infrastructures6080114.

Baştuğ et al. 2024 – Baştuğ, S., Akgül, E.F., Haralambides, H. and Notteboom, T. 2024. A decision-making framework for the funding of shipping decarbonization initiatives in non-EU countries: Insights from Türkiye. *Journal of Shipping and Trade* 9(1), 12, https://doi.org/10.1186/s41072-024-00172-1.

Bayraktar et al. 2025 – Bayraktar, M., Mollaoglu, M. and Yuksel, O. 2025. Scientometric analysis of energy efficiency indicators in maritime transportation: A systematic state-of-the-art review and implications. *Sustainability* 17(8), https://doi.org/10.3390/su17083612.

Brown et al. 2024 – Brown, M.A., Palsule, N. and Hubbs, J. 2024. Anticipating the response of climate solutions to a policy paradigm shift: Case study of the US and the state of Georgia. *Energy Strategy Reviews* 53, https://doi.org/10.1016/j.esr.2024.101411.

Díaz-Secades, L.A. 2024. Enhancement of maritime sector decarbonization through the integration of fishing vessels into IMO energy efficiency measures. *Journal of Marine Science and Engineering* 12(4), https://doi.org/10.3390/jmse12040663.

Evingür, G.A. and Osma, B. 2025. Solar photovoltaic systems: Assessing their impact on the advancement of marine decarbonization. [In:] *M.Z. Sogut, M. Koray* (Eds.), *Energy Rationality and Management for Decarbonization,* pp. 195–205. Cham: Springer, https://doi.org/10.1007/978-3-031-68497-5_10.

Fan et al. 2025 – Fan, A., Wang, Y., Yang, L., Yang, Z. and Hu, Z. 2025. A novel grey box model for ship fuel consumption prediction adapted to complex navigating conditions. *Energy* 315, https://doi.org/10.1016/j.energy.2025.134436.

Fu et al. 2025 – Fu, Q., Wu, J., Xu, H., Zhao, R. and Zhao, F. 2025. Decarbonization strategy optimization for liner fleet under emission trading policy. *Transportation Research Record* 2679(9), pp. 981–1007, https://doi.org/10.1177/03611981251341333.

Ghoneim et al. 2023 – Ghoneim, N., Colak, A.T. and Amer, A. 2023. Exploring the regulatory framework of maritime decarbonization to achieve IMO GHG emission targets. *Port-Said Engineering Research Journal* 27(1), pp. 8–14, https://doi.org/10.21608/PSERJ.2023.209426.1234.

Golub et al. 2018 – Golub, G., Kukharets, S., Tsyvenkova, N., Yarosh, Y. and Chuba, V. 2018. Experimental study into the influence of straw content in fuel on parameters of generator gas. *Eastern-European Journal of Enterprise Technologies* 5(8-95), pp. 76–86, https://doi.org/10.15587/1729-4061.2018.142159.

Grzelakowski et al. 2022 – Grzelakowski, A.S., Herdzik, J. and Skiba, S. 2022. Maritime shipping decarbonization: Roadmap to meet zero-emission target in shipping as a link in the global supply chains. *Energies* 15(17), https://doi.org/10.3390/en15176150.

Horal, L. 2022. Methodology of process-space management of the gas supply system enterprises potential in the post-industrial economy. Innovation and Sustainability 2(2), pp. 191–198, https://doi.org/10.31649/ins.2022.2.191.198.

International Maritime Organization 2033. 2023 IMO Strategy on Reduction of GHG Emissions from Ships. [Online:] https:///www.imo.org/en/ourwork/environment/pages/2023-imo-strategy-on-reduction-of-ghg-emissions-from-ships.aspx [Accessed: 2026-02-15].

Issa-Zadeh, S.B. and Garay-Rondero, C.L. 2025. Decarbonizing seaport maritime traffic: Finding hope. *World* 6(2), https://doi.org/10.3390/world6020047.

Janjghava et al. 2025 – Janjghava, R., Tsitskishvili, A. and Tsitskishvili, G. 2025. Implementing cold ironing methods in Georgian ports. [In:] *M.Z. Sogut, M. Koray* (Eds.), *Energy Rationality and Management for Decarbonization,* pp. 77–82. Cham: Springer, https://doi.org/10.1007/978-3-031-68497-5_3.

Kaiser, R. and Chowdhury, A.M. 2025. Hydrogen-powered marine vessels: A rewarding yet challenging route to decarbonization. *Clean Technologies* 7(3), https://doi.org/10.3390/cleantechnol7030068.

Karountzos et al. 2023 – Karountzos, O., Kagkelis, G. and Kepaptsoglou, K. 2023. A decision support GIS framework for establishing zero-emission maritime networks: The case of the Greek coastal shipping Network. *Journal of Geovisualization and Spatial Analysis* 7(2), 16, https://doi.org/10.1007/s41651-023-00145-1.

Klakeel et al. 2024 – Klakeel, M., Anantharaman, M., Islam, R. and Garaniya, V. 2024. Charting a greener course: A review of mature technologies for lowering vessel GHG emission. [In:] *Proceedings of the 17th International Naval Engineering Conference & Exhibition,* pp. 1–19, https://doi.org/10.24868/11183.

Kryvoruchko et al. 2021 – Kryvoruchko, O., Dmytriiev, I., Poyasnik, G., Shevchenko, I. and Levchenko, I. 2021. Transport and logistics services as a component of the transport complex and their quality management. *Problems and Prospects of Development of the Road Transport Complex: Financing, Management, Innovation, Quality, Safety – Integrated Approach* 1, pp. 42–62, https://doi.org/10.15587/978-617-7319-45-9.CH4.

Marignetti et al. 2020a – Marignetti, F., Di Stefano, R.L., Rubino, G. and Conti, P. 2020. Development and laboratory testing of a self-excited synchronous machines without permanent magnets. *Energies* 13(15), https://doi.org/10.3390/en13153966.

Marignetti et al. 2020b – Marignetti, F., Rubino, G., Boukadida, Y., Conti, P., De Gregorio, F., Iengo, E. and Giovanni Longobardi, V. 2020. Noise and vibration analysis of an inverter-fed three-phase induction motor. [In:] *2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2020*, pp. 157–161. Sorrento: Institute of Electrical and Electronics Engineers, https://doi.org/10.1109/SPEEDAM48782.2020.9161859.

Marignetti, F. and Rubino, G. 2023. Perspectives on Electric Machines with Cryogenic Cooling. *Energies* 16(7), https://doi.org/10.3390/en16072994.

Melnyk et al. 2025 – Melnyk, O., Bulgakov, M., Ocheretna, V. and Varlan, T. 2025. Hydrogen and ammonia as next-generation marine fuels in line with IMO 2050. *Machinery & Energetics* 16(3), pp. 70–80, https://doi.org/10.31548/machinery/3.2025.70.

Nisiforou et al. 2022 – Nisiforou, O., Shakou, L.M., Magou, A. and Charalambides, A.G. 2022. A roadmap towards the decarbonization of shipping: A participatory approach in Cyprus. *Sustainability* 14(4), https://doi.org/10.3390/su14042185.

Panchenko et al. 2021 – Panchenko, A., Voloshina, A., Luzan, P., Panchenko, I. and Volkov, S. 2021. Kinematics of motion of rotors of an orbital hydraulic machine. *IOP Conference Series: Materials Science and Engineering* 1021(1), https://doi.org/10.1088/1757-899X/1021/1/012045.

Psaraftis et al. 2021 – Psaraftis, H.N., Zis, T. and Lagouvardou, S. 2021. A comparative evaluation of market-based measures for shipping decarbonization. *Maritime Transport Research* 2, https://doi.org/10.1016/j.martra.2021.100019.

Pstrowska et al. 2024 – Pstrowska, K., Łużny, R., Fałtynowicz, H., Jaroszewska, K., Postawa, K., Pyshyev, S., Witek-Krowiak, A. 2024. Unlocking Sustainability: A Comprehensive Review of Up-Recycling Biomass Waste into Biochar for Environmental Solutions. *Chemistry and Chemical Technology* 18(2), pp. 211–231, https://doi.org/10.23939/chcht18.02.211.

Red'ko et al. 2019 – Red'ko, A.A., Davidenko, A.V., Pavlovskaya, A.A., Kulikova N.V., Pavlovskii, S.V., Red'ko, I.A. 2019. Numerical Investigations of the Processes of Burning a Gaseous Fuel in the Furnace of the DE-10/14 Steam Water-Tube Boiler with a Secondary Tubular Radiator. *Journal of Engineering Physics and Thermophysics* 92(2), pp. 500–507, https://doi.org/10.1007/s10891-019-01957-z.

Rubino et al. 2018 – Rubino, L., Rubino, G., Marino, P., Ladoux, P. 2018. Comparison of ultrafast chargers for plug in electrical vehicles in terms of grid integration. [In:] *SPEEDAM 2018 – Proceedings: International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, pp. 248–253. Amalfi: Institute of Electrical and Electronics Engineers, https://doi.org/10.1109/SPEEDAM.2018.8445364.

Rud, A. and Rud, A. 2025. Development and implementation of electromechanical systems for the control of soil tillage units. *Machinery & Energetics* 16(2), pp. 131–145, https://doi.org/10.31548/machinery/2.2025.131.

Sevdimaliyev et al. 2023 – Sevdimaliyev, Y.M., Salmanova, G.M., Akbarli, R.S. and Nagieva, N.B. 2023. Propagation of waves in a hydroelastic shell-viscous liquid system, in the presence of gas bubbles. *Mathematical Methods in the Applied Sciences* 46(12), pp. 12176–12189, https://doi.org/10.1002/mma.8202.

Shabib et al. 2025 – Shabib, A., Maraqa, M.A., Mustafa, S., Peng, S., Ma, G., Jia, J. and Qiu, N. 2025. Bridging theory and practice in port sustainability: A critical review of frameworks, technologies, and implementation strategies. *International Journal of Sustainable Engineering* 18(1), https://doi.org/10.1080/19397038.2025.2538856.

Shafie et al. 2025 – Shafie, P., DeChamplain, A. and Lepine, J. 2025. Technical, environmental and economic analysis of utilizing hydrogen-rich fuel in decarbonized container ships. *Sustainable Energy Fuels* 9(2), pp. 185–197, https://doi.org/10.1039/D4SE01109K.

Shi et al. 2023 – Shi, J., Zhu, Y., Feng, Y., Yang, J., Xia, C. 2023. A prompt decarbonization pathway for shipping: Green hydrogen, ammonia, and methanol production and utilization in marine engines. *Atmosphere* 14(3), https://doi.org/10.3390/atmos14030584.

Stathatou et al. 2022 – Stathatou, P.M., Bergeron, S., Fee, C., Jeffrey, P., Triantafyllou, M. and Gershenfeld, N. 2022. Towards decarbonization of shipping: Direct emissions & life cycle impacts from a biofuel trial aboard an ocean-going dry bulk vessel. *Sustainable Energy & Fuels* 6(7), pp. 1687–1697, https://doi.org/10.1039/D1SE01495A.

Tu et al. 2024 – Tu, H., Liu, Z. and Zhang, Y. 2024. Study on cost-effective performance of alternative fuels and energy efficiency measures for shipping decarbonization. *Journal of Marine Science and Engineering* 12(5), https://doi.org/10.3390/jmse12050743.

Vadachkoria et al. 2025 – Vadachkoria, G., Tsitskishvili, A. and Tsitskishvili, G. 2025. Analyzing CO_2 emission: A case study of Batumi state maritime academy. [In:] *M.Z. Sogut, M. Koray (Eds.), Energy Rationality and Management for Decarbonization,* pp. 491–495. Cham: Springer, https://doi.org/10.1007/978-3-031-68497-5_27.

Vakili et al. 2022 – Vakili, S.V., Ballini, F., Dalaklis, D. and Ölçer, A.I. 2022. A Conceptual transdisciplinary framework to overcome energy efficiency barriers in ship operation cycles to meet IMO's initial greenhouse gas strategy goals: Case study for an Iranian shipping company. *Energies* 15(6), https://doi.org/10.3390/en15062098.

Veshapidze et al. 2024 – Veshapidze, S., Kereselidze, L. and Tsirdava, N. 2024. Decarbonization of energy and the challenges of sustainable development in Georgia. *Ekonomisti* 4, pp. 132–144.

Virkovska et al. 2023 – Virkovska, A., Zaklekta, O., Lavrenchuk, V. 2023. Assessment of the export potential of national agricultural companies under the conditions of a full-scale invasion of RF. *Innovation and Sustainability* 3(4), pp. 48–57, https://doi.org/10.31649/ins.2023.4.48.57.

Voloshina et al. 2021 – Voloshina, A., Panchenko, A., Titova, O., Milaeva, I., Pastushenko, A. 2021. Prediction of Changes in the Output Characteristics of the Planetary Hydraulic Motor. [In:] *Lecture Notes in Mechanical Engineering*, pp. 744–754. Springer: Cham, https://doi.org/10.1007/978-3-030-68014-5_72.

Wang et al. 2022 – Wang, K., Guo, X., Zhao, J., Ma, R., Huang, L., Tian, F., Dong, S., Zhang, P., Liu, C., Wang, Z. 2022. An integrated collaborative decision-making method for optimizing energy consumption of sail-assisted ships towards low-carbon shipping. *Ocean Engineering* 266, https://doi.org/10.1016/j.oceaneng.2022.112810.

Wang et al. 2023 – Wang, K., Hua, Y., Huang, L., Guo, X., Liu, X., Ma, Z., Ma, R. and Jiang, X. 2023. A novel GA-LSTM-based prediction method of ship energy usage based on the characteristics analysis of operational data. *Energy* 282, https://doi.org/10.1016/j.energy.2023.128910.

Zhang et al. 2024 – Zhang, M., Tsoulakos, N., Kujala, P. and Hirdaris, S. 2024. A deep learning method for the prediction of ship fuel consumption in real operational conditions. *Engineering Applications of Artificial Intelligence* 130, https://doi.org/10.1016/j.engappai.2023.107425.

Zhou et al. 2025 – Zhou, J., Wang, Z., Chen, Y., Zhu, H. and Han, Z. 2025. Evaluation of the decarbonization effect of dual-fuel solutions for shuttle tankers using the energy efficiency design index. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, https://doi.org/10.1177/14750902251339117.

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Strategie zwiększania efektywności energetycznej statków w kontekście globalnej dekarbonizacji

Streszczenie

Znaczenie poprawy efektywności energetycznej statków morskich rośnie w związku z globalną dekarbonizacją, zaostrzającymi się normami środowiskowymi oraz rosnącymi wymaganiami dotyczącymi ograniczenia emisji gazów cieplarnianych w sektorze morskim. Celem niniejszego badania było przeprowadzenie kompleksowej analizy innowacyjnych strategii poprawy efektywności energetycznej statków z uwzględnieniem aktualnych trendów w zakresie dekarbonizacji, a także ocena ich wpływu na efektywność środowiskową i ekonomiczną transportu morskiego. W celu zbadania wpływu nowych technologii wykorzystano szereg metod, w tym analizę statystyczną, podejścia empiryczne i techniki eksperymentalne. Analiza porównawcza trzech rodzajów paliw – oleju napędowego, biopaliwa Romashka-3 i LNG – skupiała się na zużyciu, emisjach i kosztach rejsu. Wyniki pokazują, że biopaliwo zmniejsza emisję CO_2 o 19% i koszty rejsu o 6%. LNG zapewnia największą redukcję emisji – CO_2 o 20%, NO_x o 49% i SO_x o 95% – choć zwiększa koszty rejsu o 6%. Olej napędowy, charakteryzujący się najwyższą emisją i kosztem 33,7 tys. USD, jest najbardziej szkodliwy dla środowiska. Wyniki sugerują, że optymalna strategia polega na stopniowym przechodzeniu na paliwa alternatywne i rozwiązania cyfrowe w celu poprawy efektywności energetycznej bez większych kompromisów ekonomicznych. Badania te mają praktyczne znaczenie, ponieważ pomagają przedsiębiorstwom żeglugowym, operatorom flot, decydentom politycznym i organom regulacyjnym poprawić efektywność energetyczną, zmniejszyć wpływ na środowisko oraz wspierać modernizację flot i politykę zrównoważonego transportu.

Słowa kluczowe: sektor morski, paliwa alternatywne, skroplony gaz ziemny, biopaliwa, silniki okrętowe