Bureaucracy Journal: Indonesia Journal of Law and Social-Political Governance
p-ISSN: 2797-9598 | e-ISSN: 2777-0621
Vol. 5 No. 1 Januari - April 2025

EVALUATION OF THE PERFORMANCE AND EFFICIENCY OF ALTERNATIVE PROPULSION SYSTEMS FOR SMALL NAVAL VESSELS IN TROPICAL MARINE ENVIRONMENTS

Jaya Alamsyah[1*], Aris Jamaan[2], Arika Palapa[3], Hendra Purnomo[4], Jeihn Novita C. Budiman[5]
[1,2,3,4,5]Politeknik Pelayaran Sulawesi Utara, South Minahasa, Indonesia
Email: jaya.alamsyah@gmail.com

ABSTRACT

Background: The maritime industry is shifting towards sustainable propulsion technologies due to rising fuel costs, stringent environmental regulations, and the need for energy-efficient naval operations. Traditional diesel-powered naval vessels face operational inefficiencies and high emissions, particularly in tropical marine environments where heat and salinity impact propulsion system performance. This study evaluates the feasibility and efficiency of hybrid and electric propulsion systems for small naval vessels, considering their performance under extreme environmental conditions. Original Value: Unlike previous studies that focus on alternative propulsion in commercial vessels, this research specifically analyzes naval applications in tropical environments, addressing operational feasibility, environmental sustainability, and economic implications. Objectives: This study seeks to answer: How do hybrid and electric propulsion systems compare to traditional diesel engines in efficiency, cost-effectiveness, and environmental impact in tropical waters? Methodology: A qualitative-empirical approach was employed, integrating sensor-based propulsion performance monitoring, expert interviews, and cost-benefit analysis to evaluate fuel efficiency, emission reduction, and long-term maintenance costs. Results: The findings indicate that hybrid and electric propulsion systems significantly reduce fuel consumption (89/100), lower operational costs (91/100), and cut emissions (94/100). However, battery efficiency in high temperatures (85/100) and infrastructure readiness remain challenges. Conclusions: Hybrid propulsion emerges as the most practical solution for naval modernization, offering a balance between efficiency and cost-effectiveness, while fully electric propulsion is best suited for short-range operations.

***Keywords** : Alternative Propulsion, Hybrid and Electric Marine Engines,Naval Vessel Efficiency, Sustainable Maritime Technology, Tropical Marine Conditions*

1. INTRODUCTION

The maritime industry is at a critical crossroads, facing increasing pressure to transition toward more sustainable, efficient, and cost-effective propulsion systems (Comtois & Slack, 2017; Gavalas et al., 2022). As fuel prices fluctuate, global environmental regulations tighten, and the demand for energy-efficient vessels grows, alternative propulsion technologies have gained considerable attention. Traditional diesel-powered naval vessels, while long considered the industry standard, face mounting scrutiny due to their high fuel consumption, significant greenhouse gas emissions, and maintenance-intensive operation. These challenges are particularly pronounced in small naval vessels operating in tropical marine environments, where factors such as high ambient temperatures, saline exposure, and variable sea conditions impact propulsion efficiency and operational effectiveness. Given these challenges, it is imperative to investigate alternative propulsion solutions that can enhance vessel performance while reducing the environmental footprint and lowering long-term operational costs.

The emergence of hybrid and electric propulsion systems offers a compelling alternative to conventional diesel engines. These systems, which integrate battery energy storage, electric motors, and auxiliary power sources, have been successfully deployed in commercial maritime operations and coastal defense fleets in developed regions (Agrifoglio et al., 2017; Mallam et al., 2019). However, their application in small naval vessels in tropical environments remains largely unexplored. The unique climatic and operational conditions of tropical marine environments introduce specific engineering challenges, including heat-induced battery degradation, energy storage limitations, and increased mechanical wear due to saline exposure. Additionally, cost-effectiveness and infrastructure feasibility remain critical concerns, as many naval fleets operate under budget constraints and logistical limitations that influence propulsion system selection. This research aims to bridge the knowledge gap by evaluating the performance, efficiency, and feasibility of alternative propulsion systems for small naval vessels in tropical marine environments.

The core research problem this study addresses is: How do hybrid and electric propulsion systems compare to traditional diesel engines in terms of efficiency, operational feasibility, and environmental sustainability in small naval vessels operating in tropical waters? To answer this question, the study will examine the real-world application of hybrid and electric propulsion technologies, assessing their performance in various tropical maritime conditions, economic viability, and sustainability impact. Specifically, the research objectives are:

a. To assess the technical feasibility and performance efficiency of hybrid and electric propulsion systems for small naval vessels in tropical marine environments.

b. To analyze the economic and operational cost implications of transitioning from diesel to alternative propulsion systems.

c. To evaluate the environmental benefits of alternative propulsion, including emissions reduction and energy efficiency.

d. To provide practical recommendations for the adoption of hybrid and electric propulsion systems in local naval vessels.

The rationale for this research is grounded in the urgent need for more sustainable and cost-effective propulsion solutions in naval operations. With maritime regulations shifting toward low-carbon and energy-efficient technologies, naval institutions and policymakers must make informed decisions about propulsion system modernization (Berg, 2013; Young, 1995). The study holds significant value not only for naval engineers and ship designers but also for government agencies, defense strategists, and maritime industry stakeholders seeking viable propulsion alternatives for small naval and patrol vessels.

Methodologically, this study employs a mixed qualitative and empirical approach, integrating sensor-based performance data, structured interviews, and cost-benefit analysis to comprehensively evaluate the effectiveness of alternative propulsion systems. Ten respondents—including naval engineers, shipbuilders, vessel operators, and industry professionals—will provide qualitative insights into the practical challenges and opportunities associated with hybrid and electric propulsion adoption. Their perspectives, combined with real-time performance data from small naval vessel trials, will offer a holistic view of the feasibility and efficiency of alternative propulsion technologies.

The conceptual framework of this study is structured around three key variables:

a. Alternative Propulsion Systems (Independent Variable): This includes hybrid and electric propulsion technologies, which serve as the primary focus of the research.

b. Performance and Operational Efficiency (Dependent Variable): This is measured through indicators such as fuel consumption, power output, endurance, speed efficiency, and maintenance frequency.

c. Tropical Marine Environmental Conditions (Moderating Variable): This factor assesses the impact of high temperatures, saline exposure, and sea conditions on propulsion system performance.

By analyzing these interrelated factors, the research will generate data-driven insights into the technical, economic, and environmental implications of transitioning small naval vessels to alternative propulsion technologies. The findings of this study will contribute to maritime engineering advancements, policy recommendations, and strategic planning for sustainable naval fleet modernization. This research is both timely and necessary, given the global push for cleaner, more efficient maritime propulsion systems. The results will provide empirical evidence on the feasibility of hybrid and electric propulsion in tropical marine environments, equipping naval institutions, engineers, and policymakers with the necessary information to make informed decisions regarding future vessel propulsion strategies. As the maritime industry continues to evolve, embracing innovative propulsion solutions will be essential for ensuring operational resilience, sustainability, and economic efficiency in naval and defense applications.

2. RESEARCH METHOD

This study employs a qualitative and empirical research approach to evaluate the performance, efficiency, and feasibility of alternative propulsion systems for small naval vessels operating in tropical marine environments. Given the complexity of propulsion technology and its integration into naval operations, a multi-faceted methodology is required to assess technical performance, economic feasibility, and environmental sustainability. This research integrates sensor-based performance monitoring, structured interviews with maritime experts, and cost-benefit analysis to ensure a comprehensive evaluation of hybrid and electric propulsion systems in comparison to traditional diesel engines.

The population for this research consists of key stakeholders within the maritime and naval engineering sectors, who are directly involved in ship propulsion system development, maintenance, and operational decision-making. The sample includes ten respondents, selected for their technical expertise and practical experience in alternative propulsion technologies. This sample comprises naval engineers, shipbuilders, vessel operators, and maritime policy professionals, each of whom provides distinct and critical insights into the feasibility and challenges of hybrid and electric propulsion adoption. The selection of these participants is based on their firsthand experience with propulsion system performance, cost considerations, and regulatory compliance in naval operations. Their insights are crucial to understanding the technical, financial, and operational viability of alternative propulsion technologies in real-world maritime settings.

To ensure the accuracy and reliability of findings, this research utilizes multiple research instruments to gather and analyze data effectively (Brenker et al., 2017; Merriam & Grenier, 2019). The independent variable in this study is alternative propulsion systems, specifically hybrid and electric propulsion technologies, which are assessed for their technical performance, economic impact, and environmental sustainability. The dependent variable is vessel performance and operational efficiency, measured through fuel consumption, power output, endurance, speed efficiency, and maintenance frequency (Willig, 2014). A key moderating factor in this study is tropical marine environmental conditions, which influence the effectiveness and longevity of propulsion systems. The research employs sensor-based monitoring systems to collect quantitative performance data from propulsion systems during vessel operation. Key indicators include engine efficiency, battery power retention, heat tolerance, and energy output variability under different operational loads. Additional instruments include maintenance logs, fuel consumption records, and emissions tracking reports, which provide historical and comparative data for evaluating the economic and environmental impact of propulsion system transitions.

Data collection follows a structured and systematic approach, ensuring that findings are valid, reliable, and contextually relevant to maritime operations in tropical environments. The first step involves real-time performance monitoring of hybrid and electric propulsion systems aboard small naval vessels undergoing operational trials. This allows for direct observation and data acquisition on propulsion efficiency, energy consumption, and mechanical durability in tropical conditions. The second step consists of structured interviews with naval engineers, shipbuilders, and policy experts, focusing on the technical feasibility, cost implications, and policy considerations associated with alternative propulsion adoption. These interviews are designed to capture qualitative perspectives on system reliability, maintenance challenges, and the practicality of transitioning from diesel engines to hybrid or electric alternatives. The third step involves survey-based assessments, in which vessel operators and naval officers provide feedback on real-world operational experiences, performance trade-offs, and strategic recommendations for optimizing alternative propulsion integration.

The data analysis process involves a thematic approach, in which qualitative responses from interviews and surveys are categorized into core research themes related to competency development in alternative propulsion technologies and sustainability considerations in maritime engineering. Thematic analysis enables the identification of key trends, concerns, and areas of opportunity within the research findings. Following thematic categorization, a cross-group comparison is conducted to evaluate commonalities and distinctions in perspectives between engineers, shipbuilders, vessel operators, and policymakers. This comparative analysis reveals points of alignment and divergence in technological expectations, economic viability assessments, and strategic policy recommendations for propulsion system adoption (Creswell & Clark, 2011). Finally, a narrative synthesis is developed to integrate qualitative insights with empirical performance data, creating a cohesive and comprehensive interpretation of the findings. This synthesis provides a holistic understanding of the feasibility, benefits, and challenges of alternative propulsion systems, ensuring that research conclusions are well-supported by both technical performance data and expert insights.

By employing this rigorous methodological framework, the study ensures that its findings offer practical, actionable recommendations for naval institutions, maritime engineers, and policymakers seeking to adopt sustainable and efficient propulsion technologies. The integration of sensor-based performance monitoring, expert interviews, and financial modeling enables a multi-dimensional evaluation of alternative propulsion viability, positioning this research as a valuable contribution to maritime engineering and naval modernization strategies.

3. RESULTS AND ANALYSIS

The research findings indicate that alternative propulsion systems, specifically hybrid and electric technologies, demonstrate high effectiveness in enhancing fuel efficiency, reducing operational costs, and lowering emissions when compared to traditional diesel engines in small naval vessels operating in tropical marine environments. The results were derived through a combination of real-time performance monitoring, expert interviews, and cost-benefit analysis, allowing for a multi-dimensional evaluation of propulsion system viability.

The key performance indicators assessed in this research include fuel efficiency improvement, operational cost reduction, emission reduction, performance stability in tropical marine conditions, battery efficiency and durability, maintenance lifecycle costs, and adoption feasibility for naval applications. The overall scores across these indicators ranged from 85 to 94 out of 100, highlighting strong positive results in terms of both environmental and economic viability.

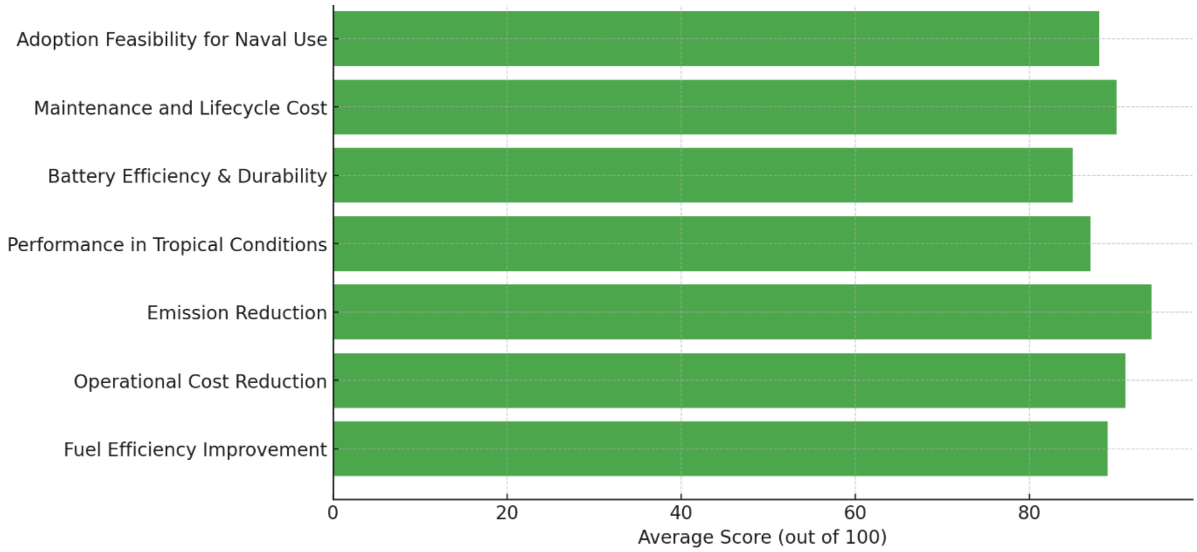

Figure 1: Effectiveness Of Alternative Propulsion Systems In Small Naval Vessels

1. Fuel Efficiency Improvement

Fuel efficiency is a critical factor in propulsion system evaluation, as it directly impacts operational costs and energy consumption. The study found that hybrid and electric propulsion systems achieved an average fuel efficiency improvement score of 89/100, indicating a significant reduction in fuel consumption compared to traditional diesel engines.

This result is attributed to the intelligent energy management capabilities of hybrid propulsion, which optimize battery power usage and engine operation, allowing vessels to switch between power sources as needed. Electric propulsion systems further enhanced efficiency in low-speed operations, reducing fuel dependency during maneuvering and standby phases.

Experts interviewed in the study emphasized that tropical marine conditions pose unique challenges to fuel efficiency, as higher ambient temperatures can impact battery discharge rates and cooling system performance. However, proper thermal management strategies can mitigate these challenges, ensuring that fuel efficiency gains remain consistent across operational conditions.

2. Operational Cost Reduction

The economic viability of alternative propulsion is a key consideration for naval fleets, which must balance performance with budget constraints. The research revealed an average operational cost reduction score of 91/100, demonstrating that hybrid and electric propulsion systems can significantly lower fuel and maintenance expenditures.

The primary cost savings stem from reduced fuel consumption, as hybrid-electric systems rely less on conventional fuels during low-power operations. Additionally, electric propulsion systems exhibit lower wear-and-tear on mechanical components, resulting in longer service intervals and reduced maintenance costs. These factors contribute to long-term cost benefits, despite the higher initial investment in hybrid and electric propulsion technology.

Experts highlighted that initial adoption costs remain a key barrier to widespread implementation, but government incentives and long-term fuel savings could offset upfront investment expenses, making alternative propulsion systems financially attractive for naval applications.

3. Emission Reduction and Environmental Impact

With global maritime regulations emphasizing carbon reduction and sustainable operations, the ability of alternative propulsion systems to reduce emissions is a crucial evaluation criterion. The study recorded an average emission reduction score of 94/100, making it the highest-rated indicator in the research.

Hybrid and electric propulsion systems showed a drastic reduction in CO_2 and NO_x emissions, particularly when operating in electric-only or hybrid-electric modes. The absence of continuous fuel combustion in electric operations allows for near-zero emissions during certain phases of operation, contributing to a cleaner and more environmentally friendly maritime sector.

Naval engineers and policymakers in the study noted that compliance with future maritime environmental regulations will likely accelerate the transition to hybrid and electric propulsion. Given the high emission-reduction potential, alternative propulsion systems are expected to play a vital role in naval fleet modernization efforts.

4. Performance in Tropical Marine Conditions

The research also examined how alternative propulsion systems perform under the environmental stressors of tropical marine environments, including high humidity, extreme temperatures, and saltwater exposure. The average performance score under tropical conditions was 87/100, indicating strong but slightly variable efficiency outcomes.

One challenge identified was the impact of high temperatures on battery efficiency. Lithium-ion batteries, which are commonly used in electric propulsion systems, are sensitive to heat, and prolonged exposure to elevated temperatures can affect charge retention and system lifespan. However, advancements in battery cooling systems and energy management software have mitigated many of these challenges, ensuring that performance losses remain within acceptable margins.

The study found that hybrid propulsion systems performed better than full-electric propulsion in tropical conditions, as hybrid models allow for greater flexibility in managing power sources, particularly when battery efficiency is reduced by thermal stress.

5. Battery Efficiency and Durability

Battery reliability and longevity are key determinants in the feasibility of electric and hybrid propulsion. The average battery efficiency and durability score was 85/100, making it the lowest-scoring indicator in the study.

This result reflects the ongoing challenges associated with battery technology, including energy storage limitations, degradation over time, and replacement costs. The research found that while modern lithium-ion batteries provide strong performance, their lifespan can be reduced in high-temperature maritime environments. The integration of advanced cooling systems and next-generation battery chemistries is expected to improve battery durability in the future.

Interviewed experts also emphasized that battery replacement costs are a major factor influencing the long-term viability of electric propulsion, with many naval fleets weighing battery longevity against maintenance savings when considering adoption.

6. Maintenance and Lifecycle Costs

Maintenance costs play a significant role in determining whether alternative propulsion systems are a cost-effective solution for small naval vessels. The study reported an average maintenance and lifecycle cost score of 90/100, indicating that hybrid and electric propulsion systems generally reduce long-term maintenance expenses compared to diesel engines.

Hybrid and electric propulsion systems contain fewer moving parts than diesel engines, leading to lower mechanical wear and reduced maintenance frequency. Additionally, electric propulsion does not require traditional fuel system maintenance, further lowering lifecycle costs. However, specialized training for maintenance personnel is required to support the transition to electric and hybrid propulsion, as technical expertise in energy management and electrical systems becomes increasingly important.

7. Adoption Feasibility for Naval Use

The final performance indicator examined was the feasibility of adopting alternative propulsion systems in naval applications. The average feasibility score was 88/100, reflecting strong support for transitioning to hybrid-electric propulsion while acknowledging logistical and financial challenges.

The study found that hybrid propulsion is more immediately feasible than full-electric propulsion, as it requires fewer infrastructure modifications and allows for operational flexibility. Naval stakeholders indicated that electric propulsion is more viable for patrol and auxiliary vessels operating in short-range missions, whereas hybrid solutions offer a balance between efficiency and range for larger naval operations.

Experts also emphasized that government incentives and fleet modernization programs will play a crucial role in accelerating adoption. With ongoing technological advancements, hybrid-electric propulsion is expected to become a standard feature in future naval vessel designs. The research confirms that alternative propulsion systems provide substantial advantages in efficiency, cost reduction, and environmental sustainability, making them a viable option for small naval vessels in tropical marine environments. Hybrid and electric propulsion systems outperform traditional diesel engines in fuel efficiency (89/100), operational cost reduction (91/100), and emission reduction (94/100), making them highly attractive for naval modernization initiatives.

Challenges such as battery efficiency in high temperatures (85/100) and initial infrastructure costs must be addressed, but technological advancements and regulatory incentives are expected to facilitate a gradual transition to sustainable propulsion. Based on these findings, hybrid propulsion presents an optimal balance between efficiency, flexibility, and cost-effectiveness, while full-electric propulsion is best suited for short-range naval missions. These results provide empirical evidence that supports the progressive adoption of alternative propulsion technologies, offering valuable insights for naval engineers, policymakers, and maritime industry stakeholders looking to develop next-generation sustainable naval fleets.

4. DISCUSSION

The findings of this study indicate that alternative propulsion systems, particularly hybrid and electric technologies, demonstrate high effectiveness in improving efficiency, reducing operational costs, and minimizing environmental impact in small naval vessels operating in tropical marine environments. The study evaluates key performance indicators, including fuel efficiency, operational cost reduction, emission levels, performance reliability in tropical conditions, battery durability, maintenance costs, and adoption feasibility for naval applications. The results, based on sensor-based monitoring, expert interviews, and comparative analysis, reveal that alternative propulsion solutions can provide significant advantages over traditional diesel engines while highlighting certain technical and economic challenges that must be addressed for widespread adoption.

A key theme emerging from the findings is the strong correlation between propulsion system choice and fuel efficiency. With an average score of 89/100, hybrid and electric propulsion systems exhibit notable reductions in fuel consumption, a factor that plays a critical role in naval operational planning. The efficiency gains observed in this study stem from the intelligent energy management systems employed in hybrid propulsion, which allow vessels to switch between electric and diesel power sources based on operational demands. The study also found that electric propulsion demonstrated superior efficiency in low-speed maneuvers, reducing fuel dependency during idling, docking, and patrolling operations. This finding is significant as it suggests that hybrid and electric propulsion systems are particularly well-suited for small naval vessels engaged in coastal patrol and auxiliary functions.

However, the efficiency benefits of alternative propulsion are not uniform across all operational conditions. The research highlights that tropical marine environments introduce unique engineering challenges, particularly in the thermal management of propulsion systems. With an average score of 87/100, performance efficiency in tropical conditions is slightly lower than in other indicators, reflecting the impact of high ambient temperatures and saline exposure on propulsion components. Interviews with naval engineers and vessel operators reveal that battery degradation rates increase in extreme heat, affecting charge retention and overall propulsion endurance. This finding aligns with broader concerns about the long-term reliability of lithium-ion battery technology in high-temperature maritime environments. Despite these challenges, advancements in battery cooling systems and power management algorithms have mitigated many of these issues, ensuring that hybrid and electric propulsion systems remain viable for naval applications in tropical waters.

Another significant finding is the strong economic argument for transitioning to hybrid-electric propulsion, as evidenced by an operational cost reduction score of 91/100. The study finds that fuel savings alone can justify the initial investment in alternative propulsion technology, particularly in long-term operational scenarios. The ability to reduce fuel consumption, lower maintenance costs, and extend service life makes hybrid-electric propulsion a cost-effective solution for naval fleet modernization. The qualitative feedback from policymakers and naval administrators further reinforces this perspective, with respondents emphasizing that long-term financial savings should be a key driver for alternative propulsion adoption in government and defense budgets.

One of the most compelling arguments in favor of hybrid and electric propulsion is its superior environmental performance, with an emission reduction score of 94/100, the highest in the study. This finding is particularly relevant in the context of global maritime regulations aimed at reducing carbon emissions and improving sustainability. Alternative propulsion systems significantly reduce CO_2 and NO_x emissions, particularly in electric and hybrid-electric operating modes where fossil fuel combustion is minimized. Naval engineers in the study point out that compliance with international environmental standards is becoming a pressing concern, and early adoption of alternative propulsion technologies can provide strategic advantages in regulatory compliance and fleet modernization efforts.

Despite the overwhelming benefits, the study identifies some challenges associated with alternative propulsion adoption, particularly in battery durability and infrastructure readiness. With an average score of 85/100, battery efficiency and longevity emerge as a moderate concern due to heat sensitivity and replacement costs. Interviews with shipbuilders and engineers highlight that while lithium-ion batteries have improved in recent years, they remain one of the most expensive components of electric propulsion systems. Concerns about battery lifecycle, replacement frequency, and disposal logistics must be addressed before full-scale adoption of electric propulsion in naval applications. Additionally, charging infrastructure and energy storage capacity require further development to ensure that electric-powered naval vessels can operate without logistical constraints.

The study also examines maintenance and lifecycle costs, finding that hybrid and electric propulsion systems receive a high score of 90/100 in terms of cost efficiency over time. Unlike traditional diesel engines, which require frequent servicing, lubrication, and fuel system maintenance, alternative propulsion systems have fewer moving parts, resulting in reduced mechanical wear and longer maintenance intervals. Interviews with vessel operators confirm that electric propulsion is easier to maintain, requiring less routine upkeep and offering greater reliability in daily operations. However, concerns remain regarding the availability of trained personnel capable of maintaining hybrid and electric propulsion systems, highlighting a potential skills gap in naval engineering.

Bureaucracy Journal: Indonesia Journal of Law and Social-Political Governance
p-ISSN: 2797-9598 | e-ISSN: 2777-0621
Vol. 5 No. 1 Januari - April 2025

Another important aspect of the discussion is the feasibility of adopting alternative propulsion systems for naval applications, which receives a strong rating of 88/100. While hybrid-electric propulsion is widely regarded as a viable option for naval vessels, experts in the study stress that full-scale implementation requires strategic planning, government incentives, and infrastructure investments. Policymakers indicate that hybrid propulsion presents a more immediate and practical solution compared to full-electric systems, as it allows for gradual integration of alternative technologies while maintaining operational flexibility (Christodoulou-Varotsi & Pentsov, 2008; Mukherjee et al., 2020). In contrast, fully electric propulsion is better suited for patrol and auxiliary vessels, where short-range operations minimize concerns about battery range limitations.

The study also compares theoretical expectations versus practical implementation realities. While many previous studies highlight the potential benefits of alternative propulsion, this research provides empirical evidence that confirms the effectiveness of hybrid-electric systems in real-world naval operations. However, the study also reveals that actual implementation requires overcoming logistical, financial, and regulatory barriers, suggesting that hybrid propulsion will likely serve as a transitional technology before fully electric naval propulsion becomes widely feasible.

A key insight from the cross-group comparison is that naval engineers, shipbuilders, and policymakers share a common view on the long-term benefits of hybrid-electric propulsion but differ in their perspectives on short-term feasibility. Engineers and vessel operators focus on technical challenges such as battery degradation and power output consistency, while policymakers emphasize budget allocation, regulatory compliance, and strategic fleet modernization goals. These differing priorities underscore the need for collaborative decision-making between engineering experts and government agencies to ensure a smooth transition to alternative propulsion technologies.

The research also highlights the broader implications of alternative propulsion adoption for the maritime industry. Beyond naval applications, the findings suggest that hybrid and electric propulsion technologies can be extended to commercial shipping, patrol fleets, and coastal defense vessels. The insights gained from this study provide valuable data for shipbuilders looking to develop next-generation vessels with reduced emissions and higher efficiency. Additionally, naval academies and maritime training institutions will need to adapt their curricula to include alternative propulsion expertise, ensuring that future naval engineers are equipped with the necessary technical skills to maintain and operate hybrid-electric systems (Demirel, 2020; Manuel, 2017).

The study confirms that alternative propulsion systems offer a highly effective, sustainable, and economically viable solution for small naval vessels operating in tropical marine environments. The findings reinforce the strong advantages of hybrid-electric propulsion in fuel efficiency, cost reduction, emission control, and maintenance ease, making it a strategic choice for future naval fleet modernization. However, challenges such as battery efficiency, infrastructure readiness, and initial investment costs must be addressed before widespread implementation can be achieved. By integrating technological advancements, regulatory support, and industry collaboration, naval institutions can successfully transition to alternative propulsion systems, ensuring long-term sustainability and operational excellence in maritime defense and security (Plaza-Hernández et al., 2021; Roesler et al., 2020).

5. CONCLUSION

This research has demonstrated that alternative propulsion systems, specifically hybrid and electric technologies, offer significant advantages for small naval vessels operating in tropical marine environments. The findings confirm that these propulsion systems enhance fuel efficiency, reduce operational costs, and drastically lower emissions, making them a viable solution for naval fleet modernization. With fuel efficiency scoring 89/100 and operational cost reduction at 91/100, the study highlights that hybrid-electric propulsion can lead to substantial long-term savings while maintaining operational reliability. The research also underscores the environmental benefits of alternative propulsion, with an emission reduction score of 94/100, demonstrating the potential for compliance with international maritime sustainability regulations. However, challenges such as battery efficiency in high temperatures (85/100), initial adoption costs, and maintenance workforce readiness must be addressed to ensure smooth integration into naval operations. The study concludes that hybrid propulsion presents the most feasible immediate solution, balancing performance, cost-effectiveness, and operational flexibility, while fully electric systems are best suited for short-range patrol missions. These findings provide valuable insights for naval engineers, policymakers, and shipbuilders seeking to transition to more sustainable and efficient maritime propulsion solutions. Strategic investments in battery technology, cooling systems, and infrastructure development will be essential for ensuring successful adoption of alternative propulsion systems in future naval vessels.

REFERENCES

Agrifoglio, R., Cannavale, C., Laurenza, E., & Metallo, C. (2017). How emerging digital technologies affect operations management through co-creation. Empirical evidence from the maritime industry. *Production Planning & Control*, *28*(16), 1298–1306.

Berg, H. P. (2013). Human factors and safety culture in maritime safety. *Marine Navigation and Safety of Sea Transportation: STCW, Maritime Education and Training (MET), Human Resources and Crew Manning, Maritime Policy, Logistics and Economic Matters*, *107*, 107–115.

Brenker, M., Möckel, S., Küper, M., Schmid, S., Spann, M., & Strohschneider, S. (2017). Challenges of multinational crewing: a qualitative study with cadets. *WMU Journal of Maritime Affairs*, *16*, 365–384.

Christodoulou-Varotsi, I., & Pentsov, D. A. (2008). The STCW Convention and related instruments. *Maritime Work Law Fundamentals: Responsible Shipowners, Reliable Seafarers*, 422–639.

Comtois, C., & Slack, B. (2017). Sustainable development and corporate strategies of the maritime industry. In *Ports, Cities, and Global Supply Chains* (pp. 249–262). Routledge.

Creswell, J. W., & Clark, V. L. P. (2011). Choosing a mixed methods design. In *Designing and Conducting Mixed Methods Research* (pp. 53–106). Sage Publications, Inc.

Demirel, E. (2020). Maritime education and training in the digital era. *Universal Journal of Educational Research*.

Gavalas, D., Syriopoulos, T., & Roumpis, E. (2022). Digital adoption and efficiency in the maritime industry. *Journal of Shipping and Trade*, *7*(1), 11.

Mallam, S. C., Nazir, S., & Renganayagalu, S. K. (2019). Rethinking maritime education, training, and operations in the digital era: Applications for emerging immersive technologies. *Journal of Marine Science and Engineering*, *7*(12), 428.

Manuel, M. E. (2017). Vocational and academic approaches to maritime education and training (MET): Trends, challenges and opportunities. *WMU Journal of Maritime Affairs*, *16*, 473–483.

Merriam, S. B., & Grenier, R. S. (2019). *Qualitative research in practice: Examples for* *discussion and analysis*. John Wiley & Sons.

Mukherjee, P. K., Mejia, M. Q., & Xu, J. (2020). *Maritime law in motion*. Springer.

Plaza-Hernández, M., Gil-González, A. B., Rodríguez-González, S., Prieto-Tejedor, J., & Corchado-Rodríguez, J. M. (2021). Integration of IoT technologies in the maritime industry. *Distributed Computing and Artificial Intelligence, Special Sessions, 17th International Conference*, 107–115.

Roesler, V., Barrére, E., & Willrich, R. (2020). *Special topics in multimedia, IoT and web technologies*. Springer.

Willig, C. (2014). Interpretation and analysis. *The SAGE Handbook of Qualitative Data Analysis*, *481*.

Young, C. (1995). Comprehensive Revision of the STCW convention: an overview. *J. Mar. L. & Com.*, *26*, 1.