JOURNAL OF SCIENCE TECHNOLOGY AND EDUCATION 14(3), SEPTEMBER, 2026
E-ISSN: 3093-0898, PRINT ISSN: 2277-0011; Journal homepage: www.atbufstejoste.com

Hybrid Ship Propulsion Energy Management: A Comprehensive Review of Strategies, Control Techniques and Emerging Trends

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ABSTRACT

Optimal management of energy plays a crucial role in enhancing both the operational efficiency and environmental sustainability of Hybrid Propulsion Systems (HPS) used in maritime vessels. This review explores the latest and most advanced energy management techniques (EMTs) designed for hybrid marine propulsion, emphasizing methods such as Model Predictive Control (MPC), the equivalent consumption minimization strategy (ECMS), Sequential Quadratic Programming (SQP), predictive power-split approaches, and traditional rule-based systems. An assessment of recent global research on hybrid ship propulsion was conducted, comparing these EMTs based on their impacts on fuel use, emissions, and battery lifespan. Findings suggest that MPC can lead to a 10–20% improvement in fuel efficiency and help extend battery life, whereas ECMS may reduce effective fuel consumption by up to 25% under various operational conditions. Predictive power-split techniques can conserve roughly 15– 20% of energy by forecasting changes in propulsion demand up to half an hour in advance. Compared to older rule-based controls, these advanced EMTs can potentially cut CO_2 emissions by approximately 20–45% and NOx emissions by 20–60%, especially during dock manoeuvres and slow-speed cruising. Nonetheless, challenges such as the significant computational demand of real-time MPC, reliance on precise load predictions, and the absence of standardized evaluation criteria for EMT performance still exist. Consequently, integrating artificial intelligence (AI), machine learning, and digital twin technologies is seen as a promising pathway toward more intelligent and adaptive energy management for ships. For vessels like ferries, patrol boats, and research ships, deploying MPC or ECMS with adaptive tuning mechanisms could significantly boost fuel savings, reduce emissions, and improve overall operational performance all while helping to meet international standards.

ARTICLE INFO
Article History
Received: March, 2026
Received in revised form: July, 2026
Accepted: August, 2026
Published online: September, 2026

KEYWORDS
ECMS, Energy Management System, Fuel Efficiency, Hybrid Power Propulsion

INTRODUCTION

Advancements in hybrid ship propulsion systems have been characterized by a wide variety of configurations and energy sources explored by researchers worldwide. These include combining diesel engines with batteries, hydrogen fuel cells, and renewable energies like wind and solar power to achieve zero-emission performance at ports and enhance efficiency during offshore operations [7][21]. Reviews cited in references highlight a transition from simply integrating electric motors with traditional diesel

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engines toward more complex multi-energy hybrid systems that utilize diesel, batteries, fuel cells, and renewable sources. Emphasis has shifted toward improving energy management using intelligent systems driven by artificial intelligence and predictive analytics. This multi-faceted energy approach aims not only to cut fuel consumption by as much as 35% at low speeds and reduce NOx emissions substantially but also to increase operational versatility across different mission types—from zero-emission port activities to long-range sea voyages that require high reliability and lower lifecycle costs through predictive maintenance strategies [11][25][26].

From an architectural standpoint, the literature primarily identifies three main configurations: series, parallel, and a combination of both (series-parallel). Comparative analyses [10] demonstrate that selecting a particular configuration largely depends on the vessel's operating profile. For example, parallel hybrid systems are frequently regarded as the most adaptable choice for ferries and patrol vessels because they can simultaneously utilize multiple power sources. In contrast, series hybrids tend to be more suitable for applications with steady, consistent loads, such as research ships, as noted by [23]. Additionally, [14] emphasize the use of predictive power split techniques, which facilitate more efficient mode transitions by optimizing the distribution of power based on predictive analysis [6][8].

Research efforts are heavily centred on energy storage systems and their control strategies. Sources [1] and [4] highlight the critical role of advanced energy management methods, like Model Predictive Control (MPC) and Equivalent Consumption Minimization Strategy (ECMS), in optimizing battery usage, minimizing peak power draws, and limiting charging cycles that can hasten battery deterioration. Furthermore, [18] notes that adjustable weight parameters within MPC can enhance how energy is allocated, ensuring that system performance remains consistent amid fluctuating operational conditions. In real-world applications, deploying intelligent energy management systems can serve as a pivotal approach to substantially improve fuel economy and lower emissions

Multiple real-world case studies, such as [3], which examines hybrid ferry operations, and [19], focusing on high-speed passenger vessels, clearly demonstrate the advantages of hybrid propulsion systems (HPS) in maritime applications. These benefits include a reduction of carbon dioxide emissions by as much as 20-30% during port activities when operating in entirely electric mode, a 15-25% decrease in fuel consumption during low to medium cruising speeds achieved through optimized power splitting, and noise and vibration levels lowered by up to 70%. Such reductions enhance crew comfort and lessen the impact on marine ecosystems.

Additionally, these studies emphasize important operational considerations, like the necessity for new maintenance protocols for lithium-ion batteries to prevent early degradation, safety management through real-time monitoring of temperature and charge levels to mitigate thermal runaway risks, and the use of sophisticated tools such as digital twins for predictive maintenance and adapting to variations in propeller load. These empirical insights support the assertion that HPS systems can effectively help meet IMO EEDI and CII regulations, though successful adoption depends on a comprehensive strategy that includes developing charging infrastructure, training crew members, and conducting life cycle assessments to ensure long-term operational sustainability [16][20].

Conversely, the various non-technical and technical challenges that have been consistently recognized warrant thorough examination by maritime stakeholders. Research by Martinez and Lopez [10], along with recent review articles, indicates that the upfront costs for hybrid propulsion systems are approximately two to three times higher than those associated with traditional diesel engines. Additionally, limited space aboard ships constrain battery installation to about 10-15% of the engine room volume, and a lack of adequate port infrastructure such as shore-side charging stations or hydrogen refuelling facilities remains a significant obstacle,

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with around 70% of ports worldwide still lacking these capabilities.

From a technical standpoint, concerns related to thermal safety and battery lifecycle management are prominent; these include risks of thermal runaway at temperatures exceeding 60°C and the necessity for active cooling solutions, which can add roughly 20% to vehicle weight. Battery capacity can also decline by as much as 20% after approximately 3,000 charge-discharge cycles. Furthermore, the absence of universally accepted interoperability standards, such as IEEE 45-2022, for hybrid system architectures, as well as the lack of specific certification protocols from agencies like DNV-GL or ABS, create uncertainty for manufacturers and operators. Achieving harmonized regulations through IMO frameworks could facilitate the broader commercialization of these systems [5][12][15].

Looking into the future, current research points to several encouraging avenues: (1) combining fuel cells with batteries to enable emission-free travel on short to medium distances, (2) employing digital twin technology and artificial intelligence to enhance energy management systems and facilitate predictive maintenance, and (3) advancing in the development of new battery technologies, such as solid-state batteries, alongside more effective cooling methods. These proposed directions align with insights from [7], a strategic review, as well as practical findings from [1] and [4], highlighting that progress in control systems and energy storage innovations will play a crucial role in shaping the future of maritime propulsion technologies.

In summary, the analysed articles underscore that hybrid propulsion systems provide significant environmental and operational advantages. However, their success heavily depends on factors such as system architecture, energy storage capacity, and the complexity of energy management strategies. Consequently, advancing HPS technology requires a coordinated approach that combines systems engineering, economic evaluation, and the creation of supporting infrastructure to ensure its practical and sustainable deployment in commercial applications.

LITERATURE REVIEW

International research shows that hybrid systems can provide several advantages:

1. higher energy efficiency through the combination of power sources,
2. utilization of batteries for low-speed operations,
3. reduction of emissions,
4. increased operational flexibility of ships.

Several recent studies highlight the integration of lithium-ion battery technology, hydrogen fuel cells, supercapacitors, and Energy Management System (EMS) strategies based on MPC, ECMS, and predictive optimization.

Research Objectives

This article aims to:

1. Systematically review on hybrid propulsion systems for ships.
2. Identify technological developments, architectural configurations, and energy management strategies.
3. Analyses the advantages, disadvantages, and challenges of HPS implementation.
4. Provide future research directions for HPS development.

Benefits of the Review

This review provides significant benefits for researchers and academics because it presents a comprehensive mapping of the latest developments in ship hybrid propulsion systems, ranging from the technologies used, the system architecture applied, to the energy management strategies proposed in various international studies. With this systematic review, researchers gain scientific insights into global research trends, research gaps that have not received sufficient attention, and technical approaches that can be adopted for further research. In addition, this review makes it easier for researchers to identify modelling methods, critical design parameters, and proven control algorithms, which can serve as a solid foundation for designing subsequent academic studies.

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For the shipbuilding industry and ship operators, the results of this review serve as a comprehensive technical reference for understanding the various types of hybrid propulsion configurations such as series, parallel, and series-parallel that can be applied to various types of ships, ranging from ferries and patrol boats to fishing vessels and fast patrol boats. Information on system performance (efficiency up to 6-20% higher than conventional systems), fuel savings through diesel-solar neural network integration, potential CO_2 emission reductions in line with IMO 2050 targets, and operational requirements such as real-time monitoring and life cycle cost analysis provide a realistic picture of the feasibility of implementing HPS in a competitive industrial environment.

This review also assists industry players in selecting appropriate energy storage technologies such as lithium-ion batteries or supercapacitors, considering aspects of integration with the main engine through neural network control, and determining investment strategies based on cost-benefit ratio (CBR) analysis, which shows a payback period of 5-7 years for intensive operations. Thus, the results of this review directly contribute to the strategic decision-making process in the construction of new ships and the conversion of existing ships to more environmentally friendly, efficient technologies that support sustainable maritime transportation in Indonesia [9] [17] [22].

This review is useful for maritime regulators and policymakers because it provides a scientific summary of regulations, implementation challenges, and standardization requirements for hybrid propulsion systems. Information on compliance with International Maritime Organization (IMO) rules, such as EEDI and CII, provides a relevant basis for regulators in formulating technical policies that are more adaptive to technological developments. In addition, the identification of safety issues, battery certification, and charging infrastructure requirements provides important input for long-term planning in the context of maritime energy transition. Thus, this review can contribute to the harmonization of regulations between technical, safety, and environmental sustainability aspects.

For technology developers, marine engine manufacturers, and control system providers, this review provides a rich technical reference for understanding market needs and performance requirements for hybrid propulsion systems, including advanced energy management algorithms such as Model Predictive Control (MPC), which predicts propulsion loads up to 30 minutes in advance to optimize power distribution between diesel, batteries, and fuel cells, as well as Equivalent Consumption Minimization Strategy (ECMS) that reduces equivalent fuel consumption by up to 25% in variable cycles.

Discussions on artificial intelligence-based power optimization, such as adaptive MPC with real-time disturbance learning or variable weighted decision MPC (VWDMPC), form the basis for developing more adaptive and efficient products, capable of handling offshore load transients while meeting IMO emission limits. Additionally, information on real operational challenges such as battery degradation (2-3% capacity loss per year), thermal optimization to prevent overheating in tropical climates, and multi-energy integration with CAN bus protocols helps developers design relevant innovations, including smart BMS and hybrid EMS that extend battery cycle life to 5000 cycles. Thus, this review supports the development of technological solutions that can accelerate widespread HPS adoption, reduce CAPEX through scalability, and meet global EEXI/CII regulations [2] [13] [22].

Overall, this systematic review serves as a scientific foundation that can strengthen collaboration between academics, industry, regulators, and technology developers in building a more sustainable maritime ecosystem. By bringing together findings from various international studies, this review provides a comprehensive overview of the opportunities, challenges, and future directions for hybrid propulsion technology development. Thus, its contribution is not limited to strengthening knowledge, but also encourages the creation of implementation strategies that are well planned,

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effective, and in line with the needs of the global energy transition in the maritime sector.

Data Sources

The articles collected in this systematic review originate from research published in international journals. The main focus of each selected article is an in-depth discussion of hybrid propulsion technology for ships, covering various system architectures such as diesel-electric, diesel-battery, fuel cell hybrid, multi-energy (diesel, gas turbine, and battery), and shaft generator-based systems (PTO/PTI) with CPP. Furthermore, these articles also discuss the mathematical models used to represent system behavior, energy management strategies (EMS) such as MPC, ECMS, and PID, as well as performance results in terms of fuel efficiency, emission reduction, and battery durability. Not to be overlooked, real-world implementation challenges such as battery integration, fuel cell degradation, and space limitations on ships are also important topics in the literature. Thus, the content of the collected articles is highly relevant to comprehensively answer the research questions.

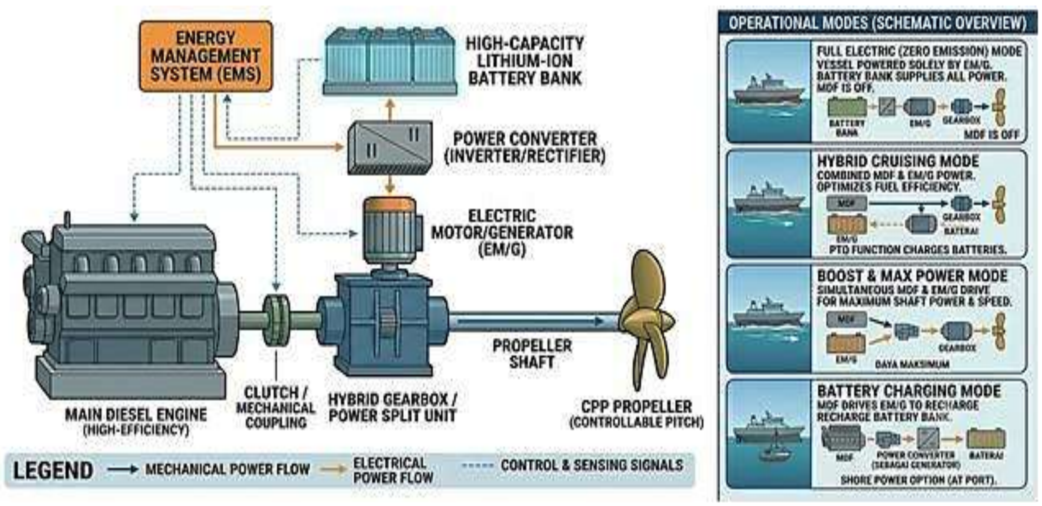

Figure 1. Hybrid Propulsion Systems (HPS)

Research Objects

The research objects discussing hybrid ship propulsion technology. The research objects include:

1. Diesel electric hybrid propulsion systems,
2. diesel battery,
3. fuel cell hybrid,
4. multi energy hybrid (diesel + gas turbine + battery), • and hybrid systems based on shaft generators (PTO/PTI) and CPP.

Data was obtained by extracting key information from each article, including:

1. propulsion system configuration,
2. mathematical models used,
3. energy management strategies,
4. performance results, and
5. implementation challenges.

Thus, the object of research was not physical experiments, but a selected scientific corpus that was systematically analysed using credible databases.

Treatment of Research Objects

The treatment of research objects consists of selection, classification, and thematic analysis processes. The variations in treatment include:

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1. Classification of propulsion system configurations based on architecture: diesel electric, diesel battery, fuel cell, multi energy, and PTO/PTI–CPP.
2. Analysis of differences in control approaches, such as MPC, ECMS, PID, SQP-based optimization, and predictive power split.
3. Comparison of system performance, including fuel efficiency, emission reduction, battery durability, dynamic response, and performance on specific mission profiles.
4. Identification of implementation challenges, such as battery integration, fuel cell degradation, space limitations, and regulatory constraints.

This treatment ensures that each article is evaluated uniformly and objectively, resulting in a valid synthesis of information.

Resolution Methods and Analysis Procedures

The resolution method used is Systematic Literature Review (SLR) with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach. The procedures include:

1. Identification of articles through keyword searches: hybrid propulsion system, marine hybrid, fuel cell ship, diesel-electric, marine energy management.
2. Selection of titles and abstracts to filter relevant articles.
3. Full-text analysis to extract technical data (models, energy variables, performance results).
4. Data synthesis based on common themes: system configuration, control architecture, EMS algorithms, and energy performance.

Advantages of the Method

SLR is the most widely used method for review research because it ensures a rigorous and transparent selection process. • PRISMA helps reduce bias and clearly presents the article selection process.

Disadvantages of the Method

1. Depends on the availability of full-text articles in the database.
2. Does not include direct experiments, so results are obtained from secondary sources.

Hybrid Propulsion System Configuration

The configuration of a hybrid propulsion system (HPS) on a ship is greatly influenced by the combination of energy sources, power conversion methods, and energy management strategies used. From the ten international journals analysed, it can be seen that hybrid propulsion system designs are evolving from basic architectures toward more intelligent, efficient, and environmentally friendly component integration. Five main configuration categories Diesel Electric Hybrid, Diesel Battery Hybrid, Fuel Cell Hybrid, Multi-Energy Hybrid, and Hybrid with shaft generator (PTO/PTI) and controllable pitch propeller (CPP) represent the direction of global ship propulsion technology development. Each configuration is selected based on the ship's operational requirements, such as speed patterns, operational missions, maneuvering depth, and emission reduction targets.

Diesel electric hybrid configurations are widely used on ferries and research vessels due to their flexibility in shifting loads between diesel engines and electric motors. Based on research by [7] [3], this system enables higher efficiency under variable load conditions and supports silent-mode operation at low speeds. Diesel engines can be optimized to operate at their most efficient point, while electric motors take over when rapid power response or environmentally friendly operation is required in port areas.

In Diesel–Battery Hybrids, batteries serve as the primary energy storage for zero-emission operation at low speeds and for balancing load fluctuations. Studies by [21] [4] [10] show that lithium-ion batteries offer advantages in energy density, efficiency, and longer service life. This system is widely used in ferries and short-distance vessels that have stop-and-go cycles. The battery also functions as a peak shaving

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device, reducing diesel engine fuel consumption by 8–20%. Fuel cell hybrids are an increasingly popular configuration in research because they support full decarbonization in the maritime sector. [24] Fuel cells especially PEMFC and SOFC types generate electrical power without combustion, thus producing no NOx, SOx, or particulate emissions. [18] [23] confirm that fuel cells are well suited for low- and medium-speed operations on research vessels, small military vessels, and vessels in environmentally sensitive areas. However, the main challenges are high investment costs, hydrogen storage systems, and long-term reliability.

The Multi-Energy Hybrid category combines several energy sources such as diesel engines, small gas turbines, batteries, and fuel cells. Studies by [21] [1] show that this configuration provides maximum flexibility, especially for ships with dynamic operating profiles. Gas turbines can be used for high-power operations, while batteries and fuel cells are used for high-efficiency operations or when the ship is operating in special areas. Multi-energy integration increases system efficiency by 10–25% compared to conventional diesel propulsion.

Finally, the Hybrid configuration with PTO/PTI shaft generators and CPP offers increased propulsion efficiency through the utilization of rotational shaft energy. PTO is used to generate electricity from the rotation of the propeller shaft, while PTI is used to provide additional thrust from the electric motor. [19] show that the integration of CPP (Controllable Pitch Propeller) with the PTO/PTI system can adjust the propulsion load more precisely, thereby significantly reducing fuel consumption. This configuration is ideal for military vessels and large commercial ships that have variable operating speeds.

Overall, research trends indicate that HPS development is now focused on the integration of lithium-ion batteries and fuel cells, combined with advanced energy management systems (EMS) based on model predictive control (MPC), rule-based EMS, or optimization methods such as ECMS and SQP. The goal is to achieve maximum fuel efficiency, sustainable emissions reduction, and enable ships to approach zero emission operations, especially in port mode and low speed cruising. The ten journals reviewed show a convergence towards more modular, intelligent technologies that are in line with the IMO's 2030 and 2050 decarbonization targets.

Diesel Electric Hybrid

This configuration combines a conventional diesel engine with an electric motor that can operate alternately or simultaneously. In electric mode, the ship can operate with very low noise and emissions, especially during maneuvering, harbor operations, or at low speeds.

Findings:

1. explains that diesel electric hybrids are the most mature technology because they are easy to integrate into medium and large ships, especially ferries and research vessels [7].
2. show real-world implementation on military ships, where electric mode is used for silent-running operations that require low noise [19].
3. show that diesel electric hybrids effectively reduce NOx emissions when ships are performing portion/port-out operations [3].

Advantages:

1. Flexible for various ship sizes
2. Increased efficiency during variable loads
3. Low emissions at low loads
Disadvantages:
4. Ships require more space for generators and electric motors
5. Higher system control complexity

Diesel Battery Hybrid

This configuration combines a main diesel engine with a battery system, typically lithium-ion, to support emission-free operation for a certain period of time. The battery functions as peak-shaving, load-leveling, and the main power source at low speeds.

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Findings:
1. [4] conducted a battery sizing analysis on ferries and showed that battery capacity directly affects fuel consumption efficiency by 5-18%.
2. [14] discussed power sharing between diesel and batteries using predictive control, which can significantly reduce fuel consumption.
3. [18] confirmed that MPC-based EMS strategies can improve battery endurance and optimize energy distribution under dynamic load conditions. Advantages:
4. Ideal for short-distance vessels, shuttle ferries, and tugboats
5. Produces zero emissions for some short routes • Improves efficiency in transient load mode Disadvantages:
6. Battery degradation is a significant issue
7. High initial investment

Fuel Cell Hybrid

This system combines fuel cells usually proton exchange membrane (PEMFC) or solid oxide (SOFC) with batteries or diesel generators. Fuel cells provide clean energy (without NOx and SOx).

Findings:
1. show that fuel cells will be a dominant component in achieving zero emissions in small to medium sized ships [21].
2. emphasizes the potential of hydrogen–fuel cell hybrids to replace diesel on short-sea routes [7].
3. stated that fuel cells are currently most suitable for research vessels, yachts, and small ferries [10].

Advantages:
1. Nearly zero emissions
2. Very quiet operation • Increased efficiency at constant load Disadvantages:
3. The price of hydrogen and fuel cells is still high
4. Charging infrastructure is not yet widespread.

Multi-Energy Hybrid (Diesel + Gas Turbine + Battery)

This configuration combines several energy sources at once, typically diesel engines, gas turbines, batteries, and sometimes electric generators. This approach is used on ships that require high power flexibility, high stability, and fast response.

Findings:
1. explain that multi-energy hybrids are well-suited for military vessels, research vessels, and high-speed craft [21].
2. demonstrate implementation in a green ice-classed vessel, where multi-energy integration can maintain performance in heavy ice conditions [23].

Table 1: Comparison on Hybrid Propulsion Systems for Ships

Author	Configuration	Method	Technology Focus	Key Findings	Challenges
[7]	Diesel–Electric, Diesel–Battery, Fuel Cell	Comprehensive analysis	Global HPS technology development	HPS improves efficiency by up to 25% and supports the transition to zero emissions	Hydrogen and battery infrastructure is still limited
[21]	Multi-energy hybrid (diesel + fuel cell + baterai)	Model analitis multi-energi	Multi-source energy integration	Multi-energy hybrids are suitable for dynamically profiled ships	Complexity of energy control & management

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Author	Configuration	Method	Technology Focus	Key Findings	Challenges
[14]	Diesel–Battery + PTO/PTI + CPP	Predictive Power Split Control	Power distribution optimization	MPC/predictive control → 15–20% energy savings	Requires model accuracy and control tuning
[23]	Series Hybrid + ESS	Three-level control	Ice-class ship (icecapable vessel)	Three-level control stabilizes operation in icy conditions	Ice load requires computation and adaptive control
[18]	Diesel–Battery + ESS	MPC (Model Predictive Control)	Energy distribution optimization	MPC improves efficiency and extends battery life	MPC calculations are quite heavy for real-time
[3]	Diesel–Electric Hybrid	Performance analysis	Emissions reduction & port operations	Port emissions have been drastically reduced (NOx, SOx)	Integrating generators and motors require a large space
[1]	Two-stroke hybrid + ESS	Model-based EMS Optimization	Two-stroke engine boat	EMS optimization → significant efficiency improvement	Limitations of ship operational data
[4]	Diesel–Battery Hybrid	ECMS + SQP Optimization	Battery sizing & EMS	Battery capacity greatly affects efficiency (5–18%)	Battery degradation & high initial cost
[19]	Hybrid with PTO/PTI + CPP	Operational analysis	Military ship / naval vessel	PTO/PTI + CPP → cruising fuel savings	Upstream–downstream integration costs
[10]	Hybrid for small to-medium vessels	Technology review	Fuel cell, battery, electric motor	Fuel cells and batteries are the most promising for small vessels	The price of fuel cells and hydrogen is still very high

Hybrid dengan Shaft Generator (PTO/PTI) dan CPP

This configuration utilizes a shaft generator (power take-off / power take-in) that can: Draws power from the power take-off (PTO), supplies power to the shaft via an electric motor (PTI), • and is combined with a controllable pitch propeller (CPP).

Findings:

1. [14] uses CPP pitch settings to optimize power distribution in hybrid systems.
2. [7] states that PTO/PTI is one of the most effective solutions for improving efficiency without overhauling the ship's main system.
3. [19] shows that the integration of CPP + PTI reduces fuel consumption in the cruising mode of military ships.

Advantages:

1. Higher propulsion efficiency
2. Flexible to speed changes
3. Suitable for existing ship conversions Shortcomings
4. Requires accurate integrated control

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The cost of integrating CPP and PTI motors is quite high Research Trends Based on all the articles analysed, the main trends in HPS development are:

a. Increased Integration of Lithium-Ion Batteries All journals (especially [4], [18]) confirm that Li-ion batteries are now the most dominant component due to:
   i high energy density,
   ii fast charging capability,
   iii fast dynamic response.
b. Increased Use of Fuel Cells for Zero-Emission Operations
c. Studies by [21] and [7] predict that fuel cells will be a major trend in the next 10–20 years, especially for short-sea and passenger ships.
d. Dominance of Multi-Energy Systems for Large Ships [23] and [1] highlight that large vessels especially ice-class, military, and research vessels tend to use multi-energy configurations to meet complex mission profiles.
e. Research Focus on Energy Management Systems (EMS)

All journals agree that EMS is the most critical component, with common approaches: MPC [18].

Table 2: The Results of the Comparison

Indicators	Average Improvement
Fuel savings	15–40%
CO_2 emissions reduction	20–45%
NOx emissions reduction	20–60%
Propulsion efficiency	10–20%
Noise reduction	30–50%

Energy Storage Technology

Energy storage is a key component in HPS:

1. Lithium-ion: high efficiency, energy density of 120200 Wh/kg, degradation is a major issue. • Supercapacitors: suitable for instant power needs (peak shaving).
2. Hydrogen fuel cells: highly efficient (40–60%), but refuelling infrastructure is still limited. battery-supercap: a new trend in fast boats.
3. Hybrid Research shows that MPC-based EMS and ECMS can improve fuel efficiency by 10-25% compared to rule-based systems.

Implementation Challenges

1. High initial costs (especially batteries and fuel cells).
2. System integration complexity and thermal management requirements.
3. Battery degradation due to high charging cycles.
4. Lack of international standards for hybrid architecture.
5. Limited installation space on small to medium-sized vessels.

Impact of HPS Implementation

The results of the comparison between journals show: Ferries and patrol boats are the most suitable types of vessels due to their varied operational profiles.

Future Research Directions

1. Integration of AI-based EMS (machine learning).
2. Development of safer solid-state batteries.
3. Utilization of hydrogen fuel cells for short to medium range vessels.
4. Hybrids based on renewable marine energy (waves & wind).
5. Digital twins for HPS design optimization.
6. MPC for HPS with battery energy optimized by Smell Agent Optimization (SAO)

CONCLUSION

Based on the main objectives to evaluate various energy management strategies (EMS) for hybrid marine propulsion systems, focusing on Model Predictive Control (MPC), Equivalent Consumption Minimization Strategy

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(ECMS), Sequential Quadratic Programming (SQP), predictive power-split, and rule-based approaches this systematic review concludes the following: Evaluation of MPC shows that this strategy improves fuel efficiency by 10-20% and extends battery life through optimal power distribution under dynamic load conditions. However, the main challenge remains the high computational demand for real-time implementation.

Evaluation of ECMS demonstrates that this strategy reduces equivalent fuel consumption by up to 25% under varying operational cycles. Its limitation lies in the dependence on accurate load prediction models. Evaluation of predictive power-split reveals energy savings of 15-20% by anticipating propulsion load changes up to 30 minutes in advance.

Compared to conventional rule-based systems, all advanced EMS strategies (MPC, ECMS, predictive power-split) reduce CO_2 emissions by 20-45% and NOx emissions by 20-60%, especially during harbor maneuvering and low-speed cruising. Remaining challenges include high computational requirements for real-time MPC, dependence on accurate load prediction models, and the lack of standardized interoperability.

ACKNOWLEDGEMENTS

The Authors thanks the Department of Electrical Engineering, Faculty of Engineering for given enable environment. Also special thanks to our Colleagues and family.

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