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Energy Management Strategies for Hybrid Ship Propulsion: A Systematic of MPC, ECMS, and Predictive Control

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Abstract**—** Effective energy management is essential for maximizing the efficiency and environmental benefits of hybrid propulsion systems (HPS) in ships. This systematic review aims to evaluate advanced energy management strategies (EMS) applied to marine HPS, focusing on model predictive control (MPC), equivalent consumption minimization strategy (ECMS), sequential quadratic programming (SQP), predictive power-split, and rule-based approaches. We collected and analyzed recent international articles on hybrid ship propulsion, then compared the performance of different EMS based on fuel efficiency, emission reduction, and battery durability. The findings show that MPC improves fuel efficiency by 10-20% and extends battery life. ECMS reduces equivalent fuel consumption by up to 25% under varying cycles. Predictive power-split algorithms achieve 15-20% energy savings by anticipating load changes up to 30 minutes ahead. Compared to conventional rule-based systems, advanced EMS reduce CO_2 emissions by 20-45% and NOx emissions by 20-60%, especially during harbor maneuvering and low-speed cruising. However, challenges remain, including high computational demands for real-time MPC, dependence on accurate load prediction models, and lack of standardized protocols. The review concludes that integrating artificial intelligence and digital twins into EMS is the most promising research direction. For ferries, patrol boats, and research vessels, implementing MPC or ECMS with adaptive tuning can significantly enhance operational performance while complying with IMO EEDI and CII regulations.

Keywords—ECMS, energy management system, fuel efficiency, hybrid ship, MPC, predictive control

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I. Introduction

Research developments on hybrid propulsion systems for ships have been marked by diversification in the topologies and energy sources studied by international researchers, including the integration of diesel with batteries, hydrogen fuel cells, and renewable energies such as wind and solar to support zero emission operations in ports and high efficiency in the open sea. [7] [21] present comprehensive reviews showing a shift in research from simply attaching electric motors to diesel engines to multi energy hybrid designs that combine diesel, batteries, fuel cells, and renewable sources, with a focus on optimizing energy management through AI based intelligent systems and predictive models. This multi energy approach not only aims to reduce fuel consumption by up to 35% at low speeds and significantly reduce NOx emissions, but also expands the flexibility of ship operations across various mission profiles from port operations requiring zero emissions to open sea operations demanding long range, high reliability, and reduced life cycle costs through predictive maintenance [11] [25] [26].

From an architectural perspective, the literature shows three dominant configurations: series, parallel, and series parallel. Comparative studies [10] confirm that the choice of configuration is highly dependent on the operating profile; parallel hybrids are often identified as the most flexible option for ferries and patrol boats due to their ability to combine power sources simultaneously, while series hybrids offer advantages in stable, constant load operations such as research vessels, as described by [23]. [14] highlight predictive power split designs that enable more efficient transitions between modes through predictive power distribution optimization [6] [8].

Energy storage components and their management are the focus of intensive research. [1] [4] emphasize the importance of energy management algorithms such as MPC and ECMS to regulate battery usage, perform peak shaving, and reduce the number of charging cycles that accelerate degradation. [18] add that variable weight settings in MPC can improve energy distribution so that system performance remains stable under dynamic operating conditions. In practical terms, intelligent EMS can be a key lever for achieving significant fuel efficiency and emission reductions.

Several empirical case studies, such [3] on hybrid ferries and [19] on high-speed passenger ships, provide clear evidence of the benefits of hybrid propulsion systems (HPS) in the field: a reduction in CO_2 emissions of up to 20-30% during port operations through pure electric mode, a 15-25% decrease in fuel consumption during low to moderate cruising phases thanks to power-

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split optimization, and a reduction in noise and vibration levels of up to 70%, which improves crew comfort and reduces the impact on marine life. These studies also highlight crucial operational aspects, including the need for new maintenance procedures for lithium-ion batteries to prevent premature degradation, battery safety management through real-time temperature and state-of-charge monitoring systems to avoid the risk of thermal runaway, and advanced instrumentation such as digital twins for predictive system health evaluation and adaptation to propeller load variations. These empirical findings support the review's claim that HPS has real potential in supporting IMO EEDI and CII regulations, but implementation requires a holistic approach that includes the integration of recharging infrastructure, crew training, and life cycle analysis to maximize long-term return on investment [16] [20].

On the other hand, the non-technical and technical barriers that have been repeatedly identified deserve in-depth attention from maritime stakeholders. Martinez & Lopez [10] and recent review articles show that the initial investment costs are 2-3 times higher than conventional diesel systems, limited ship space for batteries (up to 10-15% of engine room volume), and the readiness of port infrastructure such as shore charging or hydrogen refueling which is still lacking in 70% of global ports are major barriers to the widespread adoption of HPS. Thermal safety and battery cycle management issues, including the risk of thermal runaway at temperatures >60°C and the need for active cooling systems that add 20% weight, are highlighted as critical technical challenges by battery integration studies, with capacity degradation of up to 20% after 3,000 cycles. Additionally, the absence of IEEE 45-2022 interoperability standards for hybrid architectures and specific DNV-GL or ABS certification guidelines adds uncertainty for developers and operators, requiring IMO regulatory harmonization to accelerate commercialization [5] [12] [15].

Looking ahead, the literature suggests several promising research directions: (1) integration of fuel cell battery hybrids to support zero-emission operations on short to medium routes, (2) use of digital twins and AI for EMS optimization and predictive maintenance, and (3) development of next-generation batteries (e.g., solid-state) and more efficient cooling solutions. These recommendations are consistent between [7] strategic review and the application findings of [1] [4], indicating that advances in control and energy storage technologies will be key determinants of the success of maritime propulsion transformation.

In summary, the reviewed series of articles confirms that hybrid propulsion systems offer a powerful combination of environmental and operational benefits, but their effectiveness is greatly influenced by architectural design, storage capacity, and EMS sophistication. Therefore, the development of HPS must be treated as an integrative effort between systems engineering, economic analysis, and the development of supporting infrastructure to ensure the feasibility and sustainability of its implementation on a commercial scale.

1.1 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.

1.2 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) Analyze the advantages, disadvantages, and challenges of HPS implementation.
(4) Provide future research directions for HPS development.

1.3 Benefits of Research

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.

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].

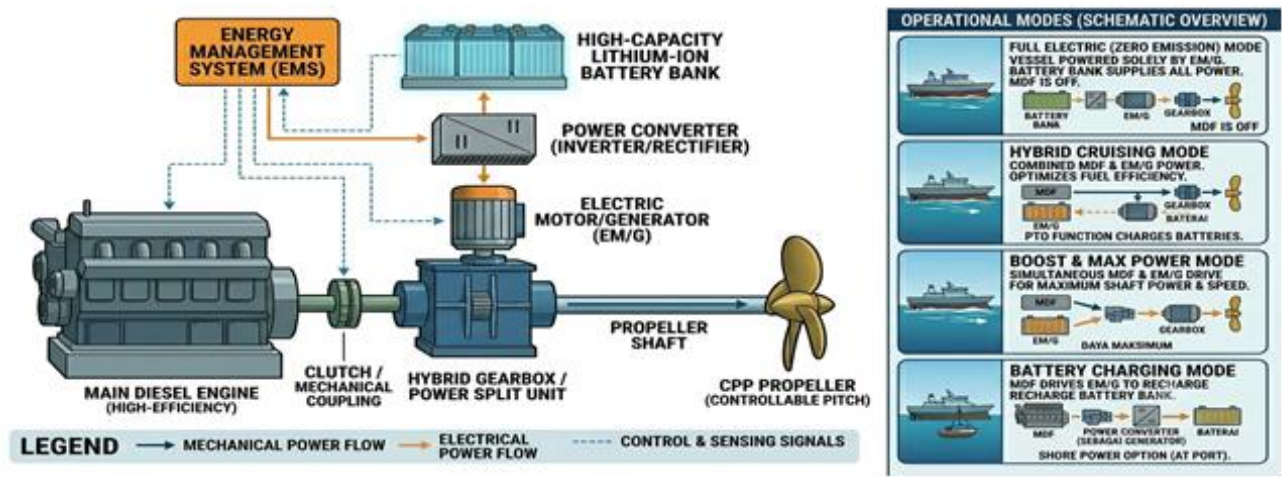

Figure 1. Hybrid Propulsion Systems (HPS)

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

II. METHOD

2.1 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.

2.2 Research Objects

The research objects discussing hybrid ship propulsion technology. The research objects include:
• Diesel electric hybrid propulsion systems,
• diesel battery,
• fuel cell hybrid,
• 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 analyzed using credible databases.

2.3 Treatment of Research Objects

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

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.

2.4 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
• Depends on the availability of full-text articles in the database.
• Does not include direct experiments, so results are obtained from secondary sources.

III. Results and Discussion

3.1 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 analyzed, 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 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.

A. 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:

- 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].
- show real-world implementation on military ships, where electric mode is used for silent-running operations that require low noise [19].
- show that diesel electric hybrids effectively reduce NOx emissions when ships are performing port-in/port-out operations [3].

Advantages:

- Flexible for various ship sizes
- Increased efficiency during variable loads
- Low emissions at low loads

Disadvantages:

- Ships require more space for generators and electric motors
- Higher system control complexity

B. 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.

Findings:

- [4] conducted a battery sizing analysis on ferries and showed that battery capacity directly affects fuel consumption efficiency by 5-18%.
- [14] discussed power sharing between diesel and batteries using predictive control, which can significantly reduce fuel consumption.
- [18] confirmed that MPC-based EMS strategies can improve battery endurance and optimize energy distribution under dynamic load conditions.

Advantages:

- Ideal for short-distance vessels, shuttle ferries, and tugboats
- Produces zero emissions for some short routes
- Improves efficiency in transient load mode

Disadvantages:

- Battery degradation is a significant issue
- High initial investment

C. 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:

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

Advantages:

- Nearly zero emissions
- Very quiet operation
- Increased efficiency at constant load

Disadvantages:

- The price of hydrogen and fuel cells is still high
- Charging infrastructure is not yet widespread

D. 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:

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

- mention that the multi-energy approach provides optimization opportunities with model based optimization in two-stroke engines [1].

Advantages:
- Highly flexible
- Suitable for extreme & multizone operations
- Provides high redundancy

Disadvantages:
- High space consumption and installation costs
- Most complex control system

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
[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 (ice-capable 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 requires 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

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

Advantages:
- Higher propulsion efficiency
- Flexible to speed changes
- Suitable for existing ship conversions Shortcomings
- Requires accurate integrated control

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:
- high energy density,
- fast charging capability,
- fast dynamic response.

b. Increased Use of Fuel Cells for Zero-Emission Operations

Journals 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.

c. 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.

d. Research Focus on Energy Management Systems (EMS)

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

• Predictive power split [14]
• ECMS + SQP optimization [4]
• Model-based optimization [1]
• Hybrid battery-supercap: a new trend in fast boats.

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%

3.2 Energy Storage Technology

Energy storage is a key component in HPS:

- Lithium-ion: high efficiency, energy density of 120-200 Wh/kg, degradation is a major issue.
- Supercapacitors: suitable for instant power needs (peak shaving).
- Hydrogen fuel cells: highly efficient (40–60%), but refuelling infrastructure is still limited. battery-supercap: a new trend in fast boats.
- Hybrid Research shows that MPC-based EMS and ECMS can improve fuel efficiency by 10-25% compared to rule-based systems.

3.3 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.

3.4 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.

3.5 Future Research Directions

- Integration of AI-based EMS (machine learning).
- Development of safer solid-state batteries.
- Utilization of hydrogen fuel cells for short to medium range vessels.
- Hybrids based on renewable marine energy (waves & wind).
- Digital twins for HPS design optimization.

IV. 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 (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 protocols.

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