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Intelligent Energy Management and Hybrid Propulsion for Ships: A Review of Configurations, AI-Based Strategies, and Decarbonization Potential

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***Abstract*—** Stringent IMO regulations targeting a 40% GHG reduction by 2030 and net-zero by 2050 have driven the maritime industry to adopt cleaner technologies, as conventional diesel propulsion often operates inefficiently with high fuel consumption and emissions. This paper aims to provide a descriptive-comparative literature review of hybrid propulsion systems for ships. The method involved examining system configurations (series, parallel, series-parallel), key components (diesel engines, fuel cells, batteries, supercapacitors), and energy management strategies (EMS), with a focus on artificial intelligence-based approaches such as Deep Reinforcement Learning (DRL) and Nonlinear Model Predictive Control (NMPC). The results show that hybrid systems can improve energy efficiency by 15–30% and significantly reduce CO_2, NO_x, and SO_x emissions compared to conventional systems, especially during zero-emission port operations. Advanced EMS, particularly DRL algorithms like Proximal Policy Optimization (PPO), enable real-time multi-objective optimization that balances fuel economy, battery health, and component longevity. However, challenges remain, including high initial investment costs, optimal sizing of hybrid energy storage systems, and limited charging infrastructure. Despite these barriers, the convergence of intelligent EMS, falling battery prices, and tightening environmental regulations positions hybrid propulsion as a key technology for sustainable maritime transportation, with future potential from waste-heat recovery systems and alternative fuels.

Keywords— Decarbonization, Energy management system, Fuel cell, Hybrid ship propulsion, IMO regulations

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I. INTRODUCTION

The main driver for the adoption of hybrid propulsion technology is the increasingly stringent international environmental regulations, particularly those set by the International Maritime Organization (IMO). The IMO has set ambitious targets, namely to reduce total annual Greenhouse Gas (GHG) emissions by at least 40% by 2030, and to achieve net-zero emissions by 2050, compared to 2008 levels [1] [22]. This effort is translated through various regulatory initiatives, such as the EEDI (Energy Efficiency Design Index) and CII (Carbon Intensity Indicator), which force the maritime industry to seek more efficient and sustainable technological solutions.

Conventional propulsion systems often operate beyond their peak efficiency point, resulting in high fuel consumption and emissions, primarily due to the use of conventional diesel engines as the primary source of ship propulsion power [3]. With the increase in international regulations regarding emission restrictions and demands for energy efficiency in the development of more environmentally friendly propulsion system technology, ship propulsion systems have developed, one of which is the hybrid propulsion system on ships [2].

Hybrid propulsion systems have emerged as a major solution to address the problem of high emissions. [3], A hybrid propulsion system is a ship propulsion system that combines two or more energy sources, such as a diesel engine with an electric motor and a battery that combines an internal combustion engine (ICE) or a new energy source (such as a Fuel Cell (FC)) with an Energy Storage System (ESS) such as a battery or supercapacitor [2] [4].

This technology allows ships to operate more flexibly according to load conditions and operational needs, so that fuel consumption can be reduced and exhaust emissions can be reduced significantly [3] [23]. In line with the global decarbonization imperative, hydrogen-electric ships have emerged as a cutting-edge solution that demands a systematic review of their hybrid power system modeling and optimization techniques [5]. This system itself has the main objective of:

1. Operate primary energy sources at maximum efficiency [6].

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2. Provide fast power for peak loads or maneuvers using ESS [7].
3. Achieve zero-emission operations in sensitive areas or during operations [7].

In addition to the three main objectives above, a recent critical advancement in hybrid propulsion is the integration of intelligent Energy Management Systems (EMS) based on artificial intelligence. Unlike conventional rule-based strategies, AI-based EMS such as Deep Reinforcement Learning (DRL) and Nonlinear Model Predictive Control (NMPC) enables real-time multi-objective optimization that dynamically balances fuel consumption, battery state-of-health, and component degradation under uncertain load conditions. These intelligent strategies have been shown to improve overall system efficiency by an additional 5–10% compared to conventional EMS, while also extending battery life and reducing life cycle costs. Therefore, the success of a hybrid propulsion system is no longer determined solely by hardware configuration, but increasingly by the sophistication of its EMS.

Several previous studies have shown that the implementation of a hybrid propulsion system can increase ship energy efficiency by more than 20% compared to conventional propulsion systems. Furthermore, hybridization of propulsion systems has also proven effective in reducing carbon dioxide (CO_2), nitrogen oxide (NO_x), and sulfur oxide (SO_x) emissions, which are the main causes of air pollution in the maritime sector [21]. Therefore, achieving the success of a hybrid propulsion system is greatly influenced by an Energy Management System (EMS) strategy, which plays a role in optimizing the distribution of power loads among various energy sources [8] [9].

The development of hybrid propulsion systems has been a major focus [3]. Summarizes the current status of power generation technologies (such as Internal Combustion Engines and Fuel Cells), energy storage components (ESS), and commonly used propulsion architectures. It also defines the selection criteria for hybrid systems based on ship type. [2]

In line with this overview, specific research has moved toward an in-depth analysis of key components. For example, [4]. Conducted a detailed analysis of a hybrid ship machinery system integrating Proton Exchange Membrane Fuel Cells (PEMFC) and a battery pack. This research focused on evaluating the performance of the energy management system under load variations. Meanwhile, aspects of innovation and efficiency optimization were raised by [10] through the design of a Fuel Cell hybrid propulsion system reinforced with Bottoming Cycle (utilization of waste heat).

Therefore, this review paper aims to critically analyze the findings [3] with the support of more specific data and models from recent studies [4] [10] to gain a comprehensive understanding of the status and direction of development of ship hybrid propulsion systems.

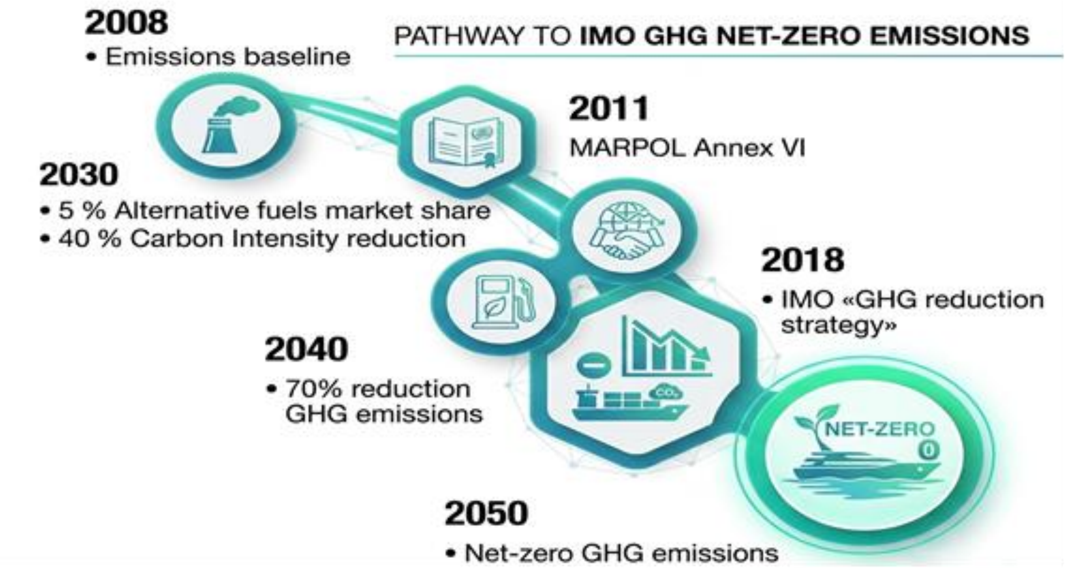

Figure 1. IMO Initiative for Ship Emission Reduction and Decarbonization Goals [2].

II. METHOD

2.1 Research Type and Approach

This research employs a systematic literature review method with a descriptive-comparative approach. This method was selected based on the need not only to collect but also to identify, evaluate, and critically synthesize findings from various previous studies relevant to hybrid propulsion systems on ships. The descriptive approach allows the researcher to explain in detail the technical configurations, components, and working principles of hybrid propulsion systems as reported in the literature [3]. Meanwhile, the comparative approach is used to compare the performance of hybrid systems against conventional systems (pure diesel) based on energy efficiency and exhaust emission parameters [7] [17]. By combining these two approaches, this research aims to provide a comprehensive overview of the current status, advantages, and challenges in the development of hybrid propulsion technology in the maritime sector, as reflected in various studies [3] [7] [8].

2.2 Data Sources and Selection Criteria

The data sources for this research were obtained from reputable national and international journals published within the last five years (2020-2025). This time frame was deliberately chosen given the rapid acceleration of hybrid propulsion technology development in the recent decade, particularly as a response to increasingly stringent International Maritime Organization (IMO) regulations, such as the targets of reducing GHG emissions by 40% by 2030 and achieving net-zero by 2050 [1] [22]. Furthermore, during the 2020–2025 period, there has been a surge in publications related to the application of artificial intelligence in Energy Management Systems (EMS) for hybrid ships, for example, the use of Deep Reinforcement Learning (DRL) and Nonlinear Model Predictive Control (NMPC) [13] [15] [25].

The key articles analyzed in depth include the comprehensive review article by Inal et al. [3] discussing the status and challenges of hybrid propulsion systems, [4] on the integration of Proton Exchange Membrane Fuel Cells (PEMFC) and batteries, [10] on efficiency improvement through a bottoming cycle, and [22] analyzing Well-to-Wake emissions of various alternative fuels. In addition, this research also refers to relevant supporting studies on renewable energy, Hybrid Energy Storage Systems (HESS) [11], and AI-based energy management strategies [9] [14]. All articles used have undergone a peer-review process to ensure scientific validity and credibility.

2.3 Research Object and Data Categorization

The object of this research is the hybrid propulsion system applied to various types of vessels based on previous studies. The vessel types covered in the review include coastal ferries [7] [18], fishing vessels, naval vessels, as well as merchant vessels and offshore supply vessels [12] [16] [17] [24].

The collected data from various sources were then grouped into five main categories to facilitate comparative analysis, namely:

1. System configuration type: series, parallel, and series-parallel (power-split) [3] and illustrated in Figure 2.
2. Energy source type: diesel, fuel cell (especially PEMFC), battery, and supercapacitor, as integrated in HESS [11].
3. Energy management strategy (EMS): from conventional rule-based to advanced AI approaches such as Deep Reinforcement Learning (DRL) with the PPO (Proximal Policy Optimization) and TD3 [14] [13], as well as Nonlinear Model Predictive Control (NMPC) [15] [25].
4. Vessel type: ferry, fishing vessel, naval vessel, merchant vessel, and offshore supply vessel.
5. Reported performance parameters: energy efficiency (15–30% improvement according to [17]), reduction of CO_2, NO_x, and SO_x emissions [7], and life cycle cost (LCC) affected by component degradation [14].

2.4 Analysis Techniques

The analysis techniques used in this research consist of two main types: descriptive analysis and comparative analysis.

a) Descriptive analysis is applied to systematically explain the basic working principles of hybrid propulsion systems, the main components (diesel engine, electric motor, battery, fuel cell, supercapacitor), and the three system configurations (series, parallel, series-parallel) as illustrated in Figure 2 [3]. This analysis also includes an explanation of the Energy Management System (EMS) and its evolution from rule-based approaches toward artificial intelligence, including the block diagram of DRL architecture shown in Figure 4 [13].

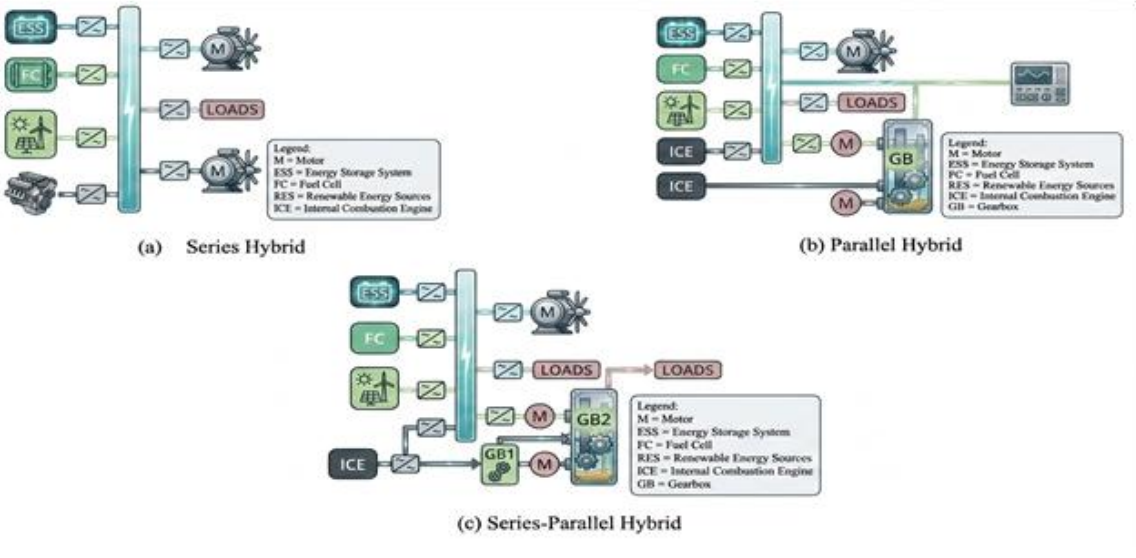

Figure 2. hybrid Propulsion System Configuration: (a). Series Hybrid [3], (b) Parallel Hybrid [3], (c) Series-Parallel Hybrid [3]

b) Comparative analysis is used to compare the performance of hybrid propulsion systems against conventional systems (pure diesel) based on energy efficiency and exhaust emission parameters. This comparison refers to empirical data from previous studies, for example, [7] who demonstrated significant emission reductions during port operations in full electric mode, [17] who reported efficiency improvements between 15% and 30%. The results of the comparative analysis are presented in tables (for instance, Table 1 showing Well-to-Wake emission factors of various fuels [22]) as well as narratives comparing the advantages and disadvantages of each system.

III. Results and Discussion

3.1 Basic Principles, Configuration, and Components of Hybrid Propulsion Systems

3.1.1 Working Principle of Ship Hybrid Propulsion System

Hybrid propulsion systems work by combining Diesel Engines, Electric Motors, and Batteries (BESS) as an integrated, regulated power source [3]. The electric motor can operate independently (full electric mode) or in conjunction with the Diesel Engine (hybrid mode), producing flexible propulsion power according to the ship's power requirements [3]. Energy from diesel generators can also be used to recharge batteries [6].

3.1.2 Hybrid Propulsion System Configuration

In general, hybrid system architecture is divided into three main configurations [22]:

- Series Hybrid: The electric motor is the sole propeller drive. The diesel engine only drives the generator to supply power to the motor and charge the battery.
- Parallel Hybrid: The electric motor and diesel engine are mechanically or electrically connected directly to drive the propeller, allowing for power boost [16].
- Series–Parallel Hybrid (Power-Split): Combines both of the above systems, offering the highest flexibility. This configuration is often used in advanced hybrid systems [22].

3.1.3 Main Components of HESS System and Technology

The main components include a Diesel Engine (ICE), an Electric Motor, and an Energy Storage System (ESS). Modern ESS has evolved into a Hybrid Energy Storage System (HESS), which integrates multiple technologies for optimal performance [11]. Significant advances in electric and hybrid propulsion technology have also been recorded on fishing vessels, demonstrating great potential for modernization and increased operational efficiency [12] [24]

- FC and Battery: The combination of Proton Exchange Membrane Fuel Cell (PEMFC) with battery offers high efficiency and zero local emissions. [4]. showed that the integration of Bottoming Cycle utilizing waste thermal energy from FC can increase the total efficiency up to 22.5% [10].
- Three-Component HESS: The use of Battery and Supercapacitor (SC) together is very effective. SC handles high-frequency load fluctuations, which not only improves performance but also extends the life of Battery and FC [7].

3.2 Smart Energy Management Strategy (EMS)

Energy Management System (EMS) is a crucial component that regulates optimal power distribution between energy sources (diesel, FC, battery) in real-time [8]. The latest developments in EMS are dominated by Artificial Intelligence (AI) based approaches, going beyond simple rule-based logic [9].

3.2.1 Deep Reinforcement Learning (DRL) and Multi-Objektif

Deep Reinforcement Learning (DRL) is very effective in stochastic (uncertain) operating environments [13].

- Multi-Objective Optimization: introduced an EMS based on the PPO (Proximal Policy Optimization) algorithm. This strategy is capable of performing dual optimization, namely reducing fuel consumption and mitigating Fuel Cell degradation, which is important for reducing Life Cycle Cost (LCC) [14].
- Near-Optimal Performance: showed that the DRL TD3 successfully achieved near-optimal cost performance on a coastal ferry, demonstrating the adaptive potential of DR [13].

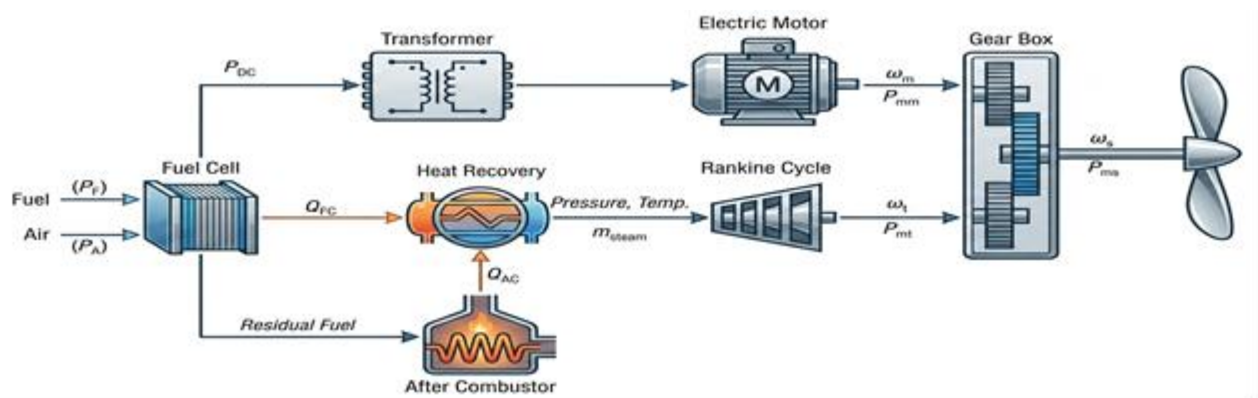

Figure 3. Schematic Diagram of Advanced Ship Hybrid Propulsion System Architecture using Fuel Cell and Bottoming Cycle for Efficiency and Environment

3.2.2 Model Predictive Control (MPC) and Battery Dynamics

- Tight Dynamic Control: For operations requiring tight prediction and constraint adherence, Nonlinear Model Predictive Control (NMPC) is very effective. Chen et al. successfully applied NMPC to regulate machine/motor torque in real-time under severe external disturbances such as random waves [15] [25]
- Battery Dynamics: In addition to power allocation, a sophisticated EMS must also protect critical components such as the battery. Yang et al. proposed a two-stage EMS that explicitly considers the battery's dynamic output characteristics (State-of-Power/SOP). This ensures safe operational limits and prevents damage to the battery [6].

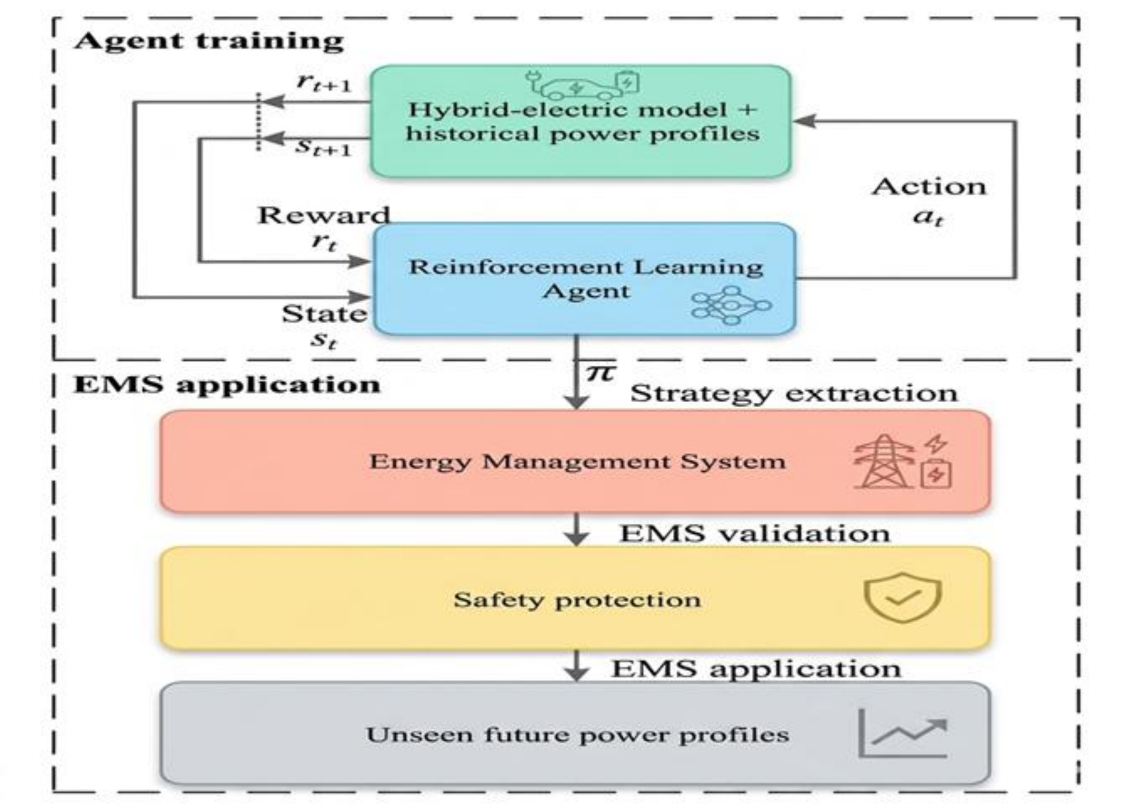

Figure 4. Block Diagram of (EMS) Architecture using Deep Reinforcement Learning (DRL) [13].

Given the complexity of modern AI-based EMS strategies and Predictive Models, validation of system performance through simulation alone is not sufficient. Due to the highly dynamic and stochastic load profiles especially on ships with high operational missions such as military vessels accurate assessment of the energy performance of hybrid propulsion systems must be assessed through an operational data-driven approach [16] [26].

Case studies adopting this methodology demonstrate the importance of data-driven performance evaluation to ensure that optimized energy management strategies are able to maintain maximum efficiency, while maintaining safe operational limits and system reliability even under the most extreme and unpredictable load conditions [16] [26]. This data-driven method provides a bridge between the theoretical efficiency achieved in design, and actual performance on the high seas.

3.3 Impact on Efficiency and Environment (Conventional Comparison)

3.3.1 Energy Efficiency and Environment

Hybrid propulsion systems have much higher energy efficiency and lower emissions than conventional systems [17]. In addition to the global impact, hybridization of coastal ferry powertrains has been shown to have a positive impact in the form of significant reductions in air pollution in port areas and coastal communities [18].

- Increased Efficiency: The implementation of a hybrid system can increase the energy efficiency of a ship by up to 15–30% [17].
- Emission Reduction: Exhaust emissions, including CO_2, NO_x, and SO_x, can be significantly reduced, especially during port operations (full electric mode) [7].
- WtW Analysis: Environmental impact assessment should be conducted from a Well-to-Wake (WtW) perspective, which covers the entire fuel life cycle. This analysis shows large variations in WtW CO_2e

emissions from hybrid-integrated alternative fuels (such as LNG and Methanol) [22].

TABLE 1.
WELL-TO-WAKE GHG EMISSION FACTORS OF VARIOUS TYPES OF SHIP PROPULSION FUELS [22].

Fuel References	MGO	LNG	Bio-LNG	Grey Methanol	Green Methanol	Grey Ammonia	Green Ammonia
	Well-to-Wake green-house gas emissions in [gCO_{2e}/MJ]						
[16]	87.0	63.0	10.0	–	10.0	–	0.0
[18,41]	90.7	76.4	–	102.9	10.4	126.3	–
[38]	93.0	87.8	–	–	–	129.8	5.4
[39]	173.9	166.0	105.4	200.3	–	–	–
[40]	81.8	–	12.5	–	33.0	–	–
[43]	–	80.9	51.1	89.4	18.2	–	–
[44]	88.9	93.8	55.5	93.8	6.0	–	–
[45]	87.8	84.5	20.3	91.2	7.4	–	–
[46]	85.5	–	–	94.2	25.6	–	–
[47]	85.3	66.6	20.0	93.5	7.6	–	–
[48]	92.0	82.1	32.1	–	–	–	36.3
[49]	–	–	–	–	–	–	–
[50]	86.7	78.9	–	95.9	4.5	–	–
[51]	91.6	84.9	33.9	–	–	–	–
# values	12	11	9	8	9	2	3
Average	88.2	79.9	29.4	94.4	13.6	–	13.9
Standard deviation	3.4	9.3	17.0	4.3	9.9	–	19.6
Minimum	81.8	63.0	10.0	89.4	4.5	126.3	0.0
Maximum	173.9	166.0	105.4	200.3	33.0	129.8	36.3
CoV [%]	3.9	11.7	57.6	4.6	72.3	–	140.8

3.3.2 Non-Energy Advantages (Conventional Comparison)

Besides efficiency, the hybrid system also offers:

- Noise and Vibration: Much lower than conventional systems, especially at low speeds or when docked (zero-emission mode) [7].
- Operational Flexibility: Ability to seamlessly switch power modes (diesel, battery, combined) [3].

3.4 Development Challenges and Opportunities

The main challenges faced in implementing a hybrid system are:

- High Initial Investment Costs: Especially for Lithium-Ion battery and Fuel Cell components [19].
- Optimal Sizing: The need to determine the optimal size of HESS components to minimize Life Cycle Cost (LCC), which requires complex metaheuristic algorithms [11].
- Infrastructure and Safety: Limited charging stations at ports and safety issues related to high-voltage electrical systems [19].

Nevertheless, the development opportunities are enormous, driven by:

- Emission Regulations: Increased IMO regulations forcing the adoption of clean technologies [20].
- EMS Advancement: Development of AI-based EMS that is increasingly intelligent and capable of optimizing multi-objective performance (cost and component life) [14].

IV. CONCLUSION

Based on the descriptive-comparative literature review conducted, hybrid propulsion systems for ships prove to be an effective solution for improving energy efficiency and reducing exhaust emissions. From a configuration perspective, the series-parallel system offers the highest flexibility, while the series system is most suitable for zero-emission port operations. The Hybrid Energy Storage System (HESS) combining batteries and supercapacitors is capable of handling high-frequency load fluctuations while extending the lifespan of the fuel cell and battery.

The success of hybrid implementation is largely determined by the advancement of Energy Management System (EMS) strategies. This review confirms that artificial intelligence-based approaches particularly Deep Reinforcement Learning with PPO and TD3 algorithms, as well as Nonlinear Model Predictive Control are capable of performing real-time multi-objective optimization while considering component degradation and dynamic operating environments. Compared to conventional rule-based EMS, AI-based approaches have been shown to provide an additional 5–10% efficiency improvement.

From a comparative standpoint, hybrid systems improve energy efficiency by 15-30% and significantly reduce CO_2, NO_x, and SO_x emissions compared to conventional systems, especially during port operations (full electric mode). However, challenges remain, including high initial investment costs, the need for optimal HESS sizing, and limited charging infrastructure. Nevertheless, declining battery prices, strengthening IMO regulations, and advances in AI-based EMS position hybrid propulsion as a key technology for sustainable maritime transportation.

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