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Evolution and Innovation of Ship Propulsion Technology: From Paddle Power to Electric and Wind-Assisted Hybrid Systems for a Sustainable Maritime Future

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Abstract**—** Ship propulsion has evolved significantly over thousands of years, from simple paddles around 40,000 BCE to modern systems including diesel engines, steam turbines, nuclear reactors, electric motors, and wind power. This paper aims to synthesize current knowledge on ship propulsion systems, highlighting technological advancements, energy efficiency, and environmental impacts. We conducted a systematic literature review using a qualitative approach and the PRISMA framework. We analyzed various studies and identified three main themes: advanced propulsion systems, propulsion optimization, and hybrid technology integration. The results show that diesel engines remain dominant, but Integrated Full Electric Propulsion (IFEP) systems with induction motors and Permanent Magnet Synchronous Motors (PMSMs) offer higher efficiency and lower emissions. Wind-assisted technologies, such as Dynarigs, Flettner rotors, and towing kites, can reduce fuel consumption by up to 50% compared to conventional systems. Nuclear propulsion enables higher operational speeds with minimal fuel replenishment. However, key challenges remain, including high initial investment costs, control system complexity, and regulatory acceptance. We conclude that the future of ship propulsion lies in hybrid configurations that optimize electric and wind power, supported by predictive computational models and fault-tolerant control to achieve cleaner, safer, and more sustainable maritime operations. Interdisciplinary collaboration is essential to accelerate this transition.

Keywords— Advanced ship propulsion, Maritime sustainability, Propulsion technology, Wind-assisted propulsion

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I. INTRODUCTION

Even 40,000 years before Christ, humans were already constructing boats and moving across the water using paddles. For nearly 35,000 years, paddling remained the primary method of propulsion until a significant discovery brought the first major advancement in ship propulsion. Despite this, sailors were reluctant to abandon the oar completely and gradually combined it with the sail. This reflects a long-standing maritime tradition of relying on proven methods and introducing new technologies only gradually. Such caution likely saved many sailors' lives in earlier times, while in modern times, abandoning this cautious approach has cost insurers considerable amounts of money. After this breakthrough, progress again slowed, with very few notable developments in ship propulsion for an extended period [1]. Both Archimedes (around 250 BC) and Leonardo da Vinci (around 1500) proposed concepts and designs that would later become important to the development of ship propulsion. Archimedes focused on the screw pump now known as the Archimedean screw which greatly influenced nineteenth-century marine engineers. However, his ideas also led to misunderstandings about propeller mechanics due to incorrect comparisons with screw threads. Leonardo da Vinci, on the other hand, produced sketches nearly 1700 years later that depicted a different type of screw-based propulsion, using fan-like blades similar to those seen in modern cooling systems [2]. A propulsion system is composed of three essential elements: an energy source (which may be stored on board as animal or fuel energy, or obtained externally from wind or solar power), an engine that converts this energy into mechanical output, and a propulsor or thruster that drives water backward to create forward motion. Without propulsion, a surface vessel cannot be steered, since rudders require water flow to function, leaving the ship vulnerable to being rolled by waves. Likewise, an underwater vessel cannot maintain a stable depth using buoyancy alone if propulsion is absent. Although it is possible to move along the seabed using crawling mechanisms, this method is rarely used due to the typically muddy ocean floor [3]. Propulsion refers to causing an object to move against natural forces, essentially counteracting the natural tendency for relative motion to diminish. Since motion is always defined relative to its surroundings,

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propulsion is sometimes equated with thrust the force that drives an object forward against opposing forces. While thrust does not always result in motion (as in the case of pushing against a wall), propulsion always involves the generation of thrust. A distinction is occasionally made between propulsion (pushing) and traction (pulling), but aside from the difference in internal stresses compression in pushing and tension in pulling both actions achieve the same goal: moving an object against natural resistance. In some contexts, however, "traction" is specifically used to describe propulsion achieved through shear forces acting on solid surfaces [4]. Today, diesel engines serve as the main source of power for propellers, and the required power and rotational speed are strongly influenced by both the ship's hull shape and the propeller's design. Consequently, achieving the most efficient solution demands a solid understanding of the key ship and diesel engine parameters that affect the overall propulsion system [5]. The propulsion system generally includes components such as diesel engines, generators, transmissions, and thrusters. In this context, a thruster refers broadly to any propeller unit. A vessel may use multiple types of thrusters. Most conventional ships have a primary propulsion unit positioned at the stern. Traditionally, this involves a shaft-line arrangement using either controllable-pitch or fixed-pitch propellers, with rudders used to steer the thrust. Another widely used option is the tunnel thruster, which is a propeller housed in a tunnel through the hull that generates a transverse force in a fixed direction. A third type is the azimuth, or rotatable, thruster, capable of delivering thrust in any chosen direction [6] [23]. One of the major factors in increasing the usable space on a ship especially on warships and cruise liners where space is highly valuable is the adoption of the Electric Ship concept. At the core of this concept is Integrated Full Electric Propulsion (IFEP). IFEP not only provides significant operational cost benefits but can also reduce initial acquisition costs in some cases. In an IFEP arrangement, the ship's propulsors are powered solely by electric motors, which draw their energy from a unified electrical system that also supplies power to all other onboard systems become integrated into a single electrical network, unlike conventional designs that typically use separate systems. A crucial technology supporting the advantages of IFEP particularly for naval applications is the development of compact electric motors. Over the past decade, substantial progress has been made in increasing motor torque density, evolving from traditional motors to advanced induction motors and permanent magnet propulsion motors [7].

a. Diesel Engine Propulsion

The early 1900s marked a period of significant experimentation and progress in diesel engine development, particularly as interest grew in applying this engine to river and coastal vessel, despite lingering doubts about their performance on long sea voyages. Rudolf Diesel patented his engine in Germany in 1892 and later secured rights in other industrialized countries, in 1894, he urged David Halley of Burmeister and Wain (B&W) to test his design, paving the way for B&W's later success in diesel engine manufacturing. Altough the *Selandia* of 1912 is often cited as the first seagoing diesel ship, the *Venoga*, built by Sulzer in 1905 for service on Lake Geneva, is considered the world;s first recorded diesel-powered vessel. Similar exeriments occurred in France with a 120 HP engine tested on the submarine *Z,* while in Russia, Diesel's patent was acquired by Ludwig Nobel's engine works in 1889, leading to the development of a 20 HP crosshead-type diesel engine in 1899 that incorporated modifications for improved manufacturing and maintenance. Diesel engines also found early use in Russia's petroleum transport industry, with the vessels *Vandal* and *Sarmat* operating in 1904–1905 and demonstrating the feasibility of diesel propulsion and the adaptability of ship designs.

Figure 1. diesel engine propulsion

Russia's abundant petroleum resources and extensive inland waterways provided favorable conditions for early adoption, even though their diesel vessels had yet to operate on the open sea. The Russo-Japanese War accelerated naval priorities but did not halt innovation, as researchers began exploring designs for long-range ocean-going diesel liners, although such vessels were not built due to wartime demands. Instead, Russia focused on expanding its navy, becoming the first to develop lightweight, fast-burning diesel-powered military vessels with reversible engines modeled after Kars-class gunboats [8] [25].

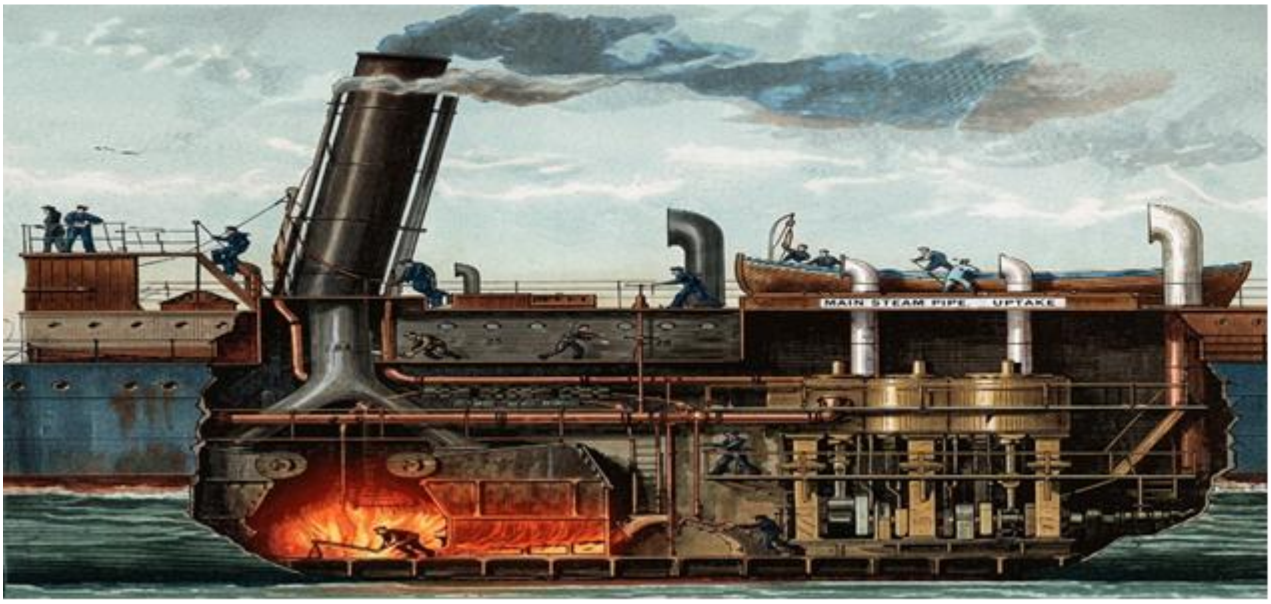

Figure 2. Steam Turbine Propulsion

b. Steam Turbine Propulsion

Steam turbines have undergone a long and dynamic evolution since their first practical development in the late 19th century, largely driven by the pioneering work of C. A. Parsons and G. de Laval. Early progress was rapid, particularly in marine propulsion and later in power generation, as throttle steam conditions steadily increased, improving both output and thermal efficiency. However, the emergence of nuclear energy as a heat source in the late 1950s reversed this trend, requiring lower steam conditions to suit reactor designs and causing a noticeable rise in unit heat rates. By then, fossil-fueled plants had largely standardized throttle conditions at around 2400 psi and 1000°F with single reheat to 1000°F. Further advancements came with once-through boilers capable of producing supercritical pressures of 3500–4500 psi. One notable example of advanced steam technology is the Eddystone No. 1 plant, which operated with exceptionally high steam conditions of 5000 psi and 1200°F at the throttle, with two stages of reheating to 1050°F. From 1950 to 1970, unit capacity increased dramatically from roughly 200 mW to 1200 mW before stabilizing in the 1970s, with newer units typically much smaller; today, expected plant sizes generally fall between 350 and 500 mW. Improvements in thermal efficiency and heat rate have been far less dramatic. Regenerative feedwater heating introduced in the 1920s produced a major drop-in heat rate, followed ter by additional reductions from steam reheating.

Incremental enhancements continued, eventually joined by combined-cycle technology using both gas and steam turbines. Yet, while unit sizes grew sixfold between 1950 and 1970, heat rates declined by less than 20%, and actual gains are even smaller when accounting for environmental requirements that consume up to about 6% of generated power. The pace of heat rate improvement is slowing, and designers are now focused on achieving modest efficiency gains through new systems as well as upgrades and repowering of existing units [9].

c. Wind Propulsion Systems

Wind represents a form of mechanical energy derived from fluid flow that originates from solar radiation through the global weather system. It provides a unique opportunity for direct propulsion, allowing air-flow forces to act directly on airfoils to drive a vessel through the water without additional energy conversion or “slip.” This method was used in seafaring for more than 5000 years at a practical, craft-based level, until the rise of coal- and oil-powered engines roughly a century ago replaced wind as the primary means of propulsion. Coincidentally, this same 100-year period has seen explosive advancements in engineering, fluid dynamics, control systems, and information technology.

Today, we thoroughly understand the principles behind wind propulsion and could apply them far more efficiently, yet this advanced knowledge has so far been mostly utilized for sports and recreational vessels. Airfoils used for wind propulsion include traditional soft sails, advanced soft sail-wings, and rigid wing-sails, each with distinct characteristics and suitable applications. Conventional sails are simple and well established; sail-wings are flexible, adjustable airfoils with variable area and camber, offering better lift-to-drag performance; and rigid wing-sails function like hard wings with flaps, delivering even higher lift-to-drag ratios [12].

Figure 3. Wind Propulsion System

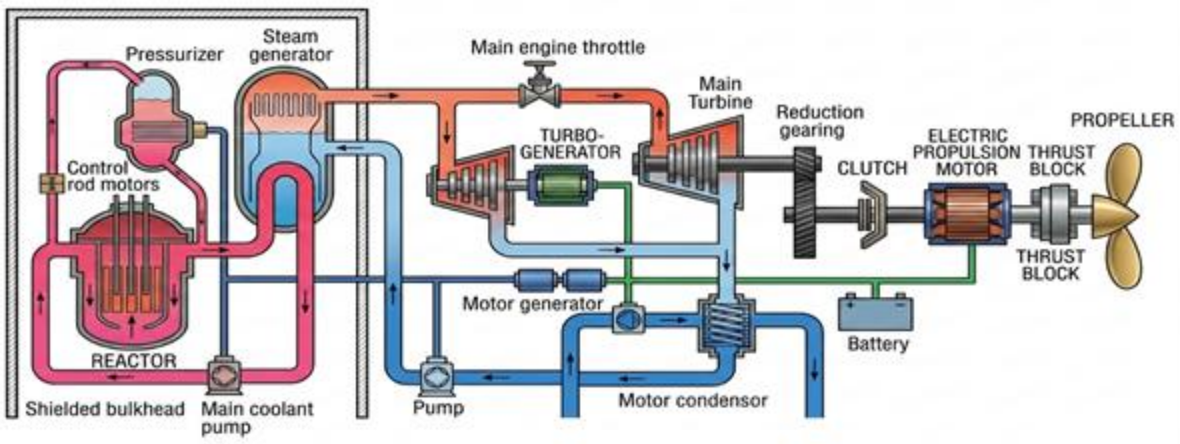

Figure 4. Nuclear Propulsion System

Wind propulsion, although seemingly an obvious solution for maritime transport, represents only one of several strategies available to reduce the sector's greenhouse gas emissions. Other mitigation approaches include switching to alternative fuels (ranging from natural gas to hydrogen), lowering vessel speed, capturing or minimizing waste heat, optimizing routes based on weather, and improving water-flow efficiency. However, due to its long historical use, wind-assisted propulsion has been extensively studied and has seen significant advancements in recent decades, largely driven by innovations from the sports sector. There are also compelling physical advantages: because wind power acts directly on the ship's hull, bypassing the substantial energy losses typically associated with propeller around 50% wind propulsion can effectively deliver up to twice the usable power compared to conventional thermal engines [13] [24]. For millennia, wind served as the primary means of propelling ships, up until fossil-fuel engines became dominant. In recent times, increasing oil prices and the pressing demand to cut CO_2 emissions have renewed interest in wind-based propulsion. Several new technologies for capturing wind energy have been introduced, and a number of companies are already offering such systems for both newly built and retrofitted vessels [14].

d. Nuclear Propulsion Systems

Escalating tensions between the United States and the Soviet Union pushed the U.S. to strengthen its military capabilities, demanding more advanced aircraft and ships. Following the devastation caused by the atomic bombs dropped on Hiroshima and Nagasaki, American efforts increasingly centered on nuclear technology. Although the United States proved that nuclear fission could power a jet engine, the program was discontinued in 1955 before a functional aircraft was created. Progress in applying nuclear fission to maritime propulsion was more successful, with modern systems still based on designs similar to those used in many land-based nuclear reactors. The U.S. Navy was the first to introduce a nuclear-powered vessel, after Congress approved the development of a nuclear propulsion system in July 1951. Captain Hyman G. Rickover, head of the Naval Reactors Branch at the Atomic Energy Commission, led this effort and ultimately became known as the father of the nuclear submarine [16]. Because nuclear fuel is inexpensive and its price remains stable, speed does not pose an economic constraint for nuclear-powered vessels. In contrast, slow steaming can lower operational costs for ships running on fossil fuels by reducing fuel consumption, but cargo owners only benefit if these savings result in reduced freight rates. Although ships typically do not carry highly time-sensitive goods, faster delivery still provides value.

Nuclear propulsion can offer higher speeds at significantly lower costs compared to conventional fossil-fueled ships. Due to the low fuel expenses, nuclear-powered vessels are economically inclined to operate at faster speeds around 20 knots for bulk carriers and 30 knots for container ships. Slow steaming emerged in recent years primarily as a way to cut fuel costs and manage surplus shipping capacity by lengthening transit times and effectively reducing the number of active vessels. However, this approach is not always well suited to the container shipping sector [17].

Nuclear-powered ships have a proven record of safety, cost-effectiveness, and strategic value. With the industrial capacity already in place, Congress must seriously consider the unique benefits of providing and maintaining a larger nuclear navy. But nuclear reactors are already expensive. Just being cheaper than current costs, which are already high, is not enough. In order to make these passively safe marine nuclear reactors cheaper, let alone get them developed at all, certain economic strategies must be employed [17].

e. Diesel-Electric Propulsion Systems

Electric propulsion systems, based on how propulsive force is generated, are generally classified into those that use electric motors and those that rely on electromagnetic propulsion. The first section of this article focuses on various types of electric motors suitable for marine propulsion, along with their corresponding speed control systems (drives), and includes a simulation of one such system. A notable category of electric motors used in propulsion applications incorporates superconducting materials in their design and is referred to as high-temperature superconducting motors (HTS motors) [19] [26]. Electric propulsion is a developing field that brings together multiple areas of expertise. Effective designs for electrically propelled vessels arise when naval architects, hydrodynamics and propulsion specialists, and electrical engineers collaborate while considering structural, operational, and economic factors. Achieving an optimized design and appropriate trade-offs requires a shared conceptual framework and a mutual understanding among all involved disciplines [20].

Diesel-electric propulsion is a broad term referring to systems that combine a diesel engine with an electrical drive setup. Although azimuth thrusters also fall under this category, they are often discussed separately due to their widespread use and advanced development compared with other diesel-electric arrangements [22]. This type of propulsion is frequently found in non-nuclear submarines; older models had to alternate between diesel and electric modes, whereas modern submarines typically operate on electric power, shifting only the power source either directly from the engine or from stored battery energy. Diesel-electric systems are often paired with azimuth thrusters, and one key benefit is the ability to rotate the propeller at very low speeds, something not achievable with conventional diesel-only systems. This capability allows a vessel to travel more slowly when necessary for instance, to avoid arriving ahead of schedule thereby maintaining the planned ETA and reducing costs associated with early berthing [21].

II. METHOD

This study utilizes a qualitative approach through a systematic literature review (SLR) to synthesize existing knowledge on ship propulsion systems and their aplications. The development of ship propulsion has been significantly influenced by regulatory frameworks and industry standards that emphasize energy efficiency and environmental sustainability.

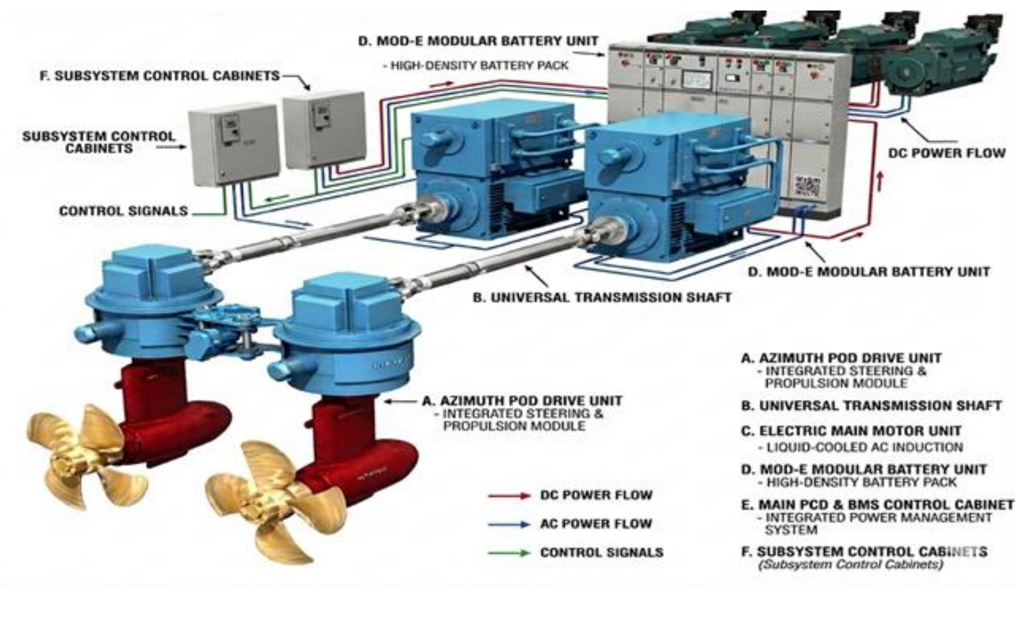

Figure 5. Diesel-Electric Propulsion System

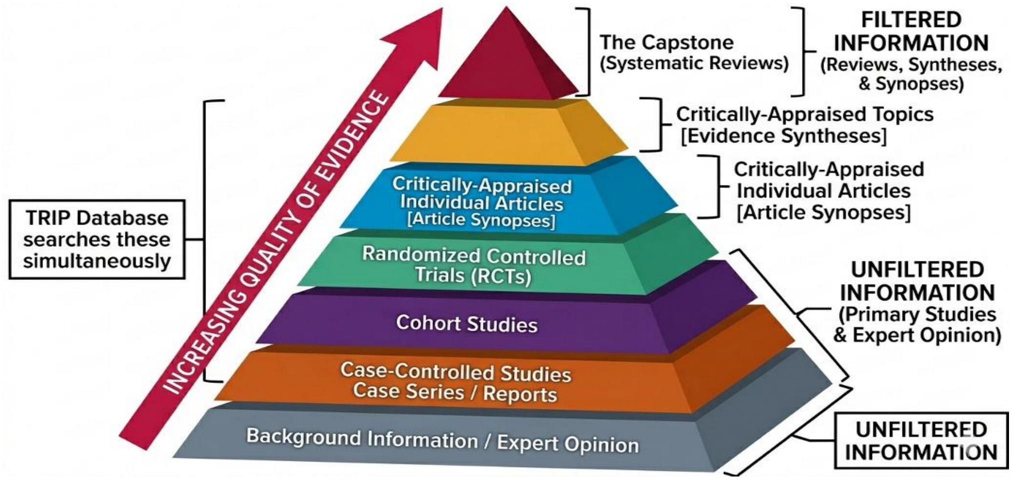

Figure 6. PRISMA Diagram

This research employs a qualitative methodology utilizing a systematic literature review (SLR) to consolidate existing insights on ship propulsion systems and evaluate their role in enhancing efficiency. The advancement of ship propulsion systems has been strongly guided by regulatory policies and industry standards that prioritize energy efficiency and environmental sustainability. At present, ship propulsion technology is striving to achieve highest efficiency and optimize performance. By applying advanced control and optimization techniques,to ensure efficient use of energy, reduce carbon emissions, and boost overall operational effectiveness, thereby fostering a more sustainable and environmentally conscious built propulsion systems. The analysis process utilized thematic coding to systematically categorize and interpret the gathered findings. Through this structured approach, three primary themes emerged that helped to organize and frame the review: advance ship propulsion systems, propulsion systems, and propulsion optimizations. This thematic structuring allowed for a coherent and comprehensive synthesis of the literature.

The validity and reliability of the study's findings were enhanced through the use of triangulation methods, which involved comparing and cross-checking data obtained from various authors, industrial contexts, and sources of publications. This multi-source verification approach helped to minimize possible biases and strengthened the overall credibility and robustness of the conclusions drawn from the reviewed literature.

To maintain the rigor and transparency of the review process, the study adopted the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to illustrate the sequential phases of article selection, including identification, screening, eligibility, and inclusion. Adhering to this systematic framework ensures methodological consistency and accountability throughout the review. The synthesized findings therefore, present a reliable, comprehensive, and up-to-date perspective on the strategic integration of Advanced Ship Prupulsion Systems. The detailed list of articles included via PRISMA methodology is presented in the following table.

TABLE 1.
FOCUS AND OUTCOMES OF ADVANCED SHIP PROPULSION RESEARCH

Focus	Outcome
Integrated Computational of a Ship Propulsion	The study demonstrates that the developed computational model accurately predicts ship propulsion performance and emissions, producing comprehensive parameter maps that support optimization of fuel consumption, operational efficiency, and emission reduction strategies.[5].
Power Electronics Based Technologies for Modern Electric and Hybrid Ship Propulsion Systems.	The article concludes that recent advancements in power electronics, electric machines, and converter topologies greatly improve the performance, energy efficiency, operational flexibility, and overall viability of modern electric and hybrid ship propulsion systems, enabling more reliable, controllable, and environmentally sustainable marine propulsion solutions.[10].
Establishing a Benchmark Ship Propulsion System for Evaluating Fault-Tolerant Control Methods.	The article produces a thoroughly validated and fully documented benchmark model of a ship propulsion system that provides the research community with a unified reference platform for rigorously developing, testing, comparing, and evaluating a wide range of fault-tolerant control methodologies spanning fault detection, isolation, diagnosis, estimation, and automatic fault accommodation thereby facilitating consistent performance assessment, enhancing methodological transparency, and accelerating advancements toward more reliable, safe, and resilient marine propulsion system designs. [11].

CONTINUED TABLE 1.
FOCUS AND OUTCOMES OF ADVANCED SHIP PROPULSION RESEARCH

Various Types of Electric Motors Used in Modern Ship Propulsion.	The article concludes that a wide range of electric motor technologies each with unique efficiency characteristics, torque capabilities, control requirements, and operational benefits can be effectively applied to ship propulsion, and it provides a thorough evaluation that helps identify the most appropriate motor types for different vessel classes and operating conditions, ultimately supporting improved performance, reliability, and energy efficiency in modern marine propulsion systems.[15].
Wind Propulsion Technologies Used in Modern Ships.	The article concludes that wind-propulsion technologies ranging from traditional sails and wing-sails to Dynarigs, Flettner rotors, and towing kites offer substantial potential for reducing fuel consumption and emissions in commercial shipping, but each technology presents distinct operational constraints, economic challenges, and integration requirements; ultimately, the review highlights that successful adoption will depend on choosing suitable technologies for new builds or retrofits, improving supportive systems such as routing software, automation, and logistics, and addressing cost, safety, and regulatory barriers, with towing kites identified as the most versatile and rapidly deployable option for accelerating the transition toward greener maritime transport. [13].

III. Results and Discussion

The findings from the three studies demonstrate significant developments in modeling, electrification, and reliability of modern ship propulsion systems. The first study developed a modular MATLAB/Simulink-based model to map performance and emission parameters under various ship operating conditions. This model successfully simulates interactions between the two-stroke diesel engine, compression system, propeller, and the ship's longitudinal surge dynamics, producing detailed maps of fuel consumption, torque, propulsive efficiency, and exhaust gas emissions such as CO_2, NO_x, and SO_2 with high accuracy. The resulting performance maps show that operating a vessel at low speeds (slow steaming) reduces fuel consumption, but does not necessarily decrease emissions in a linear manner due to reduced turbocharger efficiency and changes in combustion characteristics at lower loads. Moreover, the generated performance maps are proven useful for optimizing route planning and vessel speed to minimize energy consumption and CO_2 emissions throughout a voyage [5]. The second study by Reusser provides a comprehensive perspective on the application of power electronics and electric drives in modern propulsion systems. Advances in multilevel converter technologies, multiphase induction motors, and permanent-magnet synchronous motors (PMSMs) have enabled substantial improvements in propulsion efficiency, reductions in machinery footprint, and significant emission reductions through the integration of full-electric or hybrid electric power systems onboard ships. Modern systems such as the Integrated Power System (IPS) allow gas turbine or diesel generators to operate at optimal efficiency, as the electrical power can be distributed flexibly between propulsion and hotel loads. Real-world implementations, such as those on the HMS Queen Elizabeth aircraft carrier, demonstrate how the combination of two 35 MW gas turbine generators and 20 MW induction motors yield efficient, responsive, and highly redundant propulsion performance. These findings emphasize that the shift toward ship electrification is driven not only by efficiency demands but also by compliance with IMO 2020 regulations requiring strict reductions in sulfur and greenhouse gas emissions [10]. Meanwhile, the third study by Izadi-Zamanabadi focuses on reliability aspects through the development of a propulsion-system benchmark for fault-tolerant control (FTC). The presented model incorporates diesel engine dynamics, shaft-system behavior, controllable pitch propeller (CPP) characteristics, and a hierarchical control structure consisting of a governor, pitch control, speed control, and overload protection modules. The study identifies six fault scenarios, including pitch sensor failures, shaft speed pick-up failures, hydraulic leakage, and reduced diesel torque output. Several of these faults such as loss of pitch sensor signal or shaft-speed sensor failure are considered highly critical due to their potential to produce uncontrolled acceleration, thereby increasing collision risks. This benchmark offers a realistic platform for testing Fault Detection and Isolation (FDI) algorithms and control reconfiguration strategies. The importance of FTC is increasing as modern propulsion systems grow more complex, particularly in electric or hybrid-electric vessels where system reliability depends heavily on sensors, actuators, and power-electronic converters [18]. The review of the two documents reveals that current ship propulsion research is progressively moving toward integrating large-scale electric motor systems with modern wind-assisted propulsion technologies to improve energy efficiency and reduce emissions. Findings from Motors for Ship Propulsion indicate that several motor technologies namely induction motors, synchronous motors, permanent magnet synchronous motors (PMSM), and doubly-fed machines (DFM) stand out as the leading candidates for marine propulsion. Induction motors have demonstrated high reliability and suitability for low-speed, high-torque operation, as evidenced by their application on advanced naval ships such as the USS Zumwalt. Synchronous motors provide slightly higher efficiency and the capability to operate at a leading power factor, making them compatible with load commutated inverters commonly used in high-power electric propulsion systems. PMSMs have gained relevance due to the use of high-flux Neodymium-Iron-

Boron magnets, which significantly increase flux density and eliminate rotor copper losses, enabling compact designs with high torque density and improved overall efficiency. DFM technology also offers substantial advantages, particularly its wide operating ranges from sub-synchronous to super-synchronous speeds and its requirement for only one-third converter rating, thereby reducing system cost and improving efficiency for variable-speed propulsion applications [15].

In contrast, findings from the Wind Propulsion Technologies Review highlight the potential of modern wind-assisted systems to reduce fuel consumption and support the maritime sector's decarbonization efforts. Traditional sails operate based on pressure differences between the intrados and extrados surfaces resulting from variations in airflow velocity, producing aerodynamic lift that can be harnessed as propulsion force. Despite their effectiveness, traditional sails require extensive manual handling and skilled operation, limiting their suitability for large commercial vessels. More advanced technologies such as the Dynarig offer improved operational efficiency, ease of automation, and enhanced structural rigidity, although they remain costly to install and exhibit reduced performance when sailing upwind. Towing kites, especially dynamic variants, can deliver substantial propulsion assistance without imposing significant structural loads on the vessel, but their successful operation depends on sophisticated automated control systems and precise response to rapidly shifting wind conditions, posing notable technical challenges. Overall, wind-assisted ship propulsion (WASP) technologies show strong potential to reduce fuel consumption and emissions, yet widespread adoption remains limited by regulatory barriers, operational complexities, and the need for standardized safety frameworks within the maritime industry [13] [24].

TABLE 2.
MODERN SHIP PROPULSION FINDINGS

Technology Focus	Advantages	Challenges & Limitations	Implementation Examples
Integrated Power System (IPS) & Electric Motors (Induction, PMSM, DFM)	High efficiency, compact motor designs, flexible power distribution, and lower emissions compliant with IMO 2020 regulations	System reliability depends heavily on complex power-electronic converters, sensors, and actuators.	HMS Queen Elizabeth (35 MW gas turbines & 20 MW induction motors); USS Zumwalt.
System Reliability & Fault-Tolerant Control (FTC)	Provides a safe hierarchical control structure; detects and isolates critical faults (e.g., pitch/speed sensors) to prevent collisions.	Requires the development of complex and precise Fault Detection and Isolation (FDI) algorithms.	Benchmark modeling with hierarchical control (speed control, pitch control, overload protection).
Wind-Assisted Ship Propulsion (Dynarigs & Towing Kites)	Significantly reduces fuel consumption and supports decarbonization efforts in commercial shipping.	High installation costs (Dynarigs), reduced upwind performance, and reliance on sophisticated automation (Towing Kites) amidst regulatory barriers.	Automated rigid wing-sails (Dynarigs) and dynamic towing kites.

IV. CONCLUSION

Based on the objectives stated in the abstract namely to synthesize current knowledge on ship propulsion systems, highlighting technological advancements, energy efficiency, and environmental impacts the following conclusions are drawn:

1. Synthesis of Current Knowledge: This systematic literature review has successfully integrated existing research on ship propulsion, tracing its evolution from manual paddles and traditional sails to modern diesel, steam turbine, nuclear, electric, and wind-assisted systems. The findings confirm that diesel engines remain dominant, but emerging technologies such as Integrated Full Electric Propulsion (IFEP), Permanent Magnet Synchronous Motors (PMSMs), and high-temperature superconducting (HTS) motors offer superior performance and lower emissions.
2. Technological Advancements: Key innovations identified include:
   - Electric propulsion with advanced induction motors, PMSMs, and doubly-fed machines (DFM), enabling compact, high-torque-density designs.
   - Wind-assisted propulsion systems (WAPS) such as Dynarigs, Flettner rotors, and towing kites, capable of reducing fuel consumption by up to 50%.
   - Nuclear propulsion, providing high operational speeds with minimal fuel replenishment, though constrained by high costs and regulatory hurdles.
   - Fault-tolerant control (FTC) systems and predictive computational models that enhance reliability and operational safety.
3. Energy Efficiency: The review highlights that hybrid configurations combining electric and wind power, supported by real-time optimization algorithms and digital twins, can significantly improve overall energy efficiency. Slow steaming reduces fuel use but does not proportionally lower emissions due to combustion inefficiencies at low loads. Integrated Power Systems (IPS) allow flexible power distribution, optimizing both propulsion and hotel loads.
4. Environmental Impacts: Modern propulsion technologies directly address IMO 2020 and 2050 decarbonization targets. IFEP and wind-assisted

systems substantially reduce CO_2, NO_x, and SO_2 emissions. Nuclear propulsion offers zero-emission operation, while alternative fuels (hydrogen, ammonia, biofuels) present additional pathways for sustainable shipping. However, challenges such as high initial costs, control complexity, and regulatory acceptance remain barriers to widespread adoption.

5. The future of ship propulsion lies in hybrid and optimized systems that integrate electric motors, wind assistance, and predictive control. Interdisciplinary collaboration—encompassing naval architecture, electrical engineering, control systems, and environmental policy—is essential to accelerate the transition toward cleaner, safer, and more sustainable maritime operations.

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