Frontiers in Science and Engineering **Volume 6 Issue 5, 2026**
ISSN: 2710-0588

A Review on the Research of Marine Electric Propulsion Systems

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Abstract

Marine electric propulsion system is a core technology at the intersection of shipping low-carbonization, ship intellectualization and comprehensive electrification. Compared with traditional mechanical propulsion, electric propulsion is not a simple replacement of diesel engines with electric motors. Instead, it takes generator sets, energy storage devices, fuel cells, shore power interfaces, ship power grids, power electronic converters, propulsion motors, propellers/podded thrusters and energy management systems as the core, forming a ship integrated energy system with multi-energy sources, multi-loads and multiple constraints. Its main advantages include flexible layout, improved efficiency under low load, enhanced redundancy and maneuverability, and easy access to new energy sources such as batteries and fuel cells. Meanwhile, it still faces challenges including low battery energy density, thermal runaway risks, poor reliability of power electronic devices, electromagnetic compatibility issues, insufficient port energy supply infrastructure and difficulties in full-life-cycle carbon emission accounting. This paper reviews the research background, significance, system architecture, key equipment, energy management strategies, typical applications, safety specifications, technical bottlenecks and development trends of marine electric propulsion systems, and conducts comparative analysis on various circuit topologies and application scenarios based on published literature. The review indicates that in the coming period, pure electric and battery hybrid propulsion will be preferentially applied to coastal short-distance vessels, inland waterway ships, harbor tugs, ferries and engineering working ships. In contrast, ocean-going merchant ships will mostly adopt a progressive electrification route combining low/zero-carbon fuel main engines, shaft power generation, energy storage peak shaving, shore power connection and digital energy management.

Keywords

Marine electric propulsion; Integrated power system; Hybrid power ship; Battery energy storage; Fuel cell; energy management; Low-carbon shipping.

1. Development Background, Basic Concepts and Technical Classification

International shipping undertakes most of the transportation tasks in global trade, yet it is also one of the major sources of greenhouse gas emissions. According to the Fourth IMO Greenhouse Gas Study, global shipping greenhouse gas emissions accounted for approximately 2.89% of total anthropogenic greenhouse gas emissions in 2018, and showed an upward trend from 2012 to 2018[1]. Driven by global emission reduction goals, port environmental regulations and fluctuating fuel costs, ship power systems are gradually transforming from single fossil fuel mechanical transmission to a new form featuring multi-energy coupling, electric power transmission and intelligent management. The 2023 IMO GHG Reduction Strategy stipulates that the share of zero or near-zero greenhouse gas emission technologies, fuels and energy sources applied in international shipping shall reach at least 5% and strive for 10% by 2030, and sets the joint goal of achieving net-zero greenhouse gas emissions around 2050[2]. Against such a backdrop, electric propulsion systems have evolved from an optional solution for specific ship types into a fundamental platform for green ship design.

Traditional ship propulsion generally adopts diesel engines or gas turbines to directly drive propellers through reduction gears and shafting systems. It boasts mature technology, short transmission chain, high efficiency and abundant maintenance experience. Nevertheless, when ships operate under variable load, low speed, frequent start-stop, dynamic positioning or port berthing and departing conditions for a long time, the main engine often deviates from its high-efficiency operating range, which adversely affects fuel economy, emission performance and maneuverability. By contrast, marine electric propulsion realizes speed decoupling between prime movers and propellers via the energy flow of prime mover-generator-ship power grid-frequency converter-propulsion motor-propulsor. This enables generator sets to start, stop and operate optimally flexibly according to load demands, and provides accessible interfaces for integrating batteries, supercapacitors, fuel cells, shore power and other new energy sources.

Therefore, the core value of marine electric propulsion lies not merely in driving propellers with electric motors, but in equipping ships with a reconfigurable, expandable and optimizable energy platform. It can improve the operational efficiency and comfort of tugs, ferries, cruise ships, offshore engineering vessels and research ships under complex working conditions, support the integrated electric propulsion and high-energy weapon loads of naval vessels, and realize connection with shore power systems, intelligent dispatching and carbon emission accounting systems. From the perspective of academic research, this field covers ship power engineering, automatic control, power electronics, electrical machinery, energy storage safety, thermal management, reliability engineering and relevant regulations and standards, presenting distinct systematic engineering characteristics. This paper sorts out the whole technical system in the form of engineering review.

Marine electric propulsion system can be defined as a propulsion system taking electric energy as the intermediate carrier. Its upstream energy sources include diesel engines, gas turbines, LNG engines, fuel cells, batteries, shore power and renewable energy. The intermediate links consist of ship power grids and power conversion devices, while the downstream parts cover propulsion motors, shafting systems and podded thrusters. Electric energy functions for energy convergence, load distribution, control decoupling and fault isolation within the system. Compared with mechanical transmission, electric propulsion transforms the rigid mechanical connection between energy supply and propulsion load into controllable electrical connection, which is the fundamental reason why it can adapt to diverse energy sources, various loads and complex operating conditions.

In terms of energy configuration, electric propulsion is roughly classified into diesel-electric propulsion, gas turbine-electric propulsion, combined diesel and gas turbine electric propulsion, battery hybrid propulsion, pure battery propulsion and fuel cell hybrid propulsion. Diesel-electric propulsion mainly generates power via fossil fuels and drives propulsors by motors, which is applicable to vessels with drastic load fluctuations or high requirements for cabin layout, redundancy and maneuverability. Battery hybrid propulsion equips battery systems on the basis of conventional generator sets, improving overall efficiency through peak shaving and valley filling, spinning reserve replacement, low-speed zero-emission navigation and load ramp support. Pure battery propulsion is primarily adopted for inland waterway ships, ferries, sightseeing vessels and partial harbor workboats featuring short voyage distance, fixed routes and definite shore charging conditions. Fuel cell hybrid propulsion converts energy such as hydrogen, methanol reforming fuel and ammonia into electric power, which features low noise, low vibration and zero or near-zero emission potential. Nevertheless, its development is still restricted by fuel storage and transportation, operating cost, service life and imperfect relevant specifications.

In terms of power grid structure, marine electric propulsion systems are divided into AC power distribution, DC power distribution and hybrid AC/DC power distribution. Most traditional diesel-electric vessels adopt medium or low-voltage AC busbars to supply power to propulsion motors through transformers and frequency converters. With the popularization of batteries, fuel cells and high-power variable-frequency propulsion technologies, DC power grids have attracted increasing attention. DC power distribution reduces multi-level power conversion links and facilitates the parallel connection of variable-speed generator sets, energy storage units and DC loads, which is especially suitable for variable-speed generators and energy storage systems. Nevertheless, DC systems feature rapid rise of short-circuit current, difficult fault clearance and complicated selective protection design, imposing higher requirements on circuit breakers, busbar segmentation, insulation monitoring and system-level fault analysis.

In terms of propulsion actuators, marine electric propulsion can adopt shaft-mounted motors, podded thrusters, azimuth thrusters, rim-driven thrusters or pump-jet propulsors. Shaft-mounted motors are suitable for the retrofitting of conventional merchant ships and high-power propulsion. Podded thrusters place the motor inside an external hull pod, enabling 360-degree steering and optimizing maneuverability as well as cabin layout. Azimuth thrusters are widely applied in tugs, offshore engineering vessels and dynamically positioned ships. Different types of propulsors affect hydrodynamic efficiency, noise level, maintenance modes, redundancy configuration and cabin space arrangement. Therefore, the design of electric propulsion systems must be comprehensively considered in combination with ship type, navigation route, maneuvering requirements and maintenance strategies.

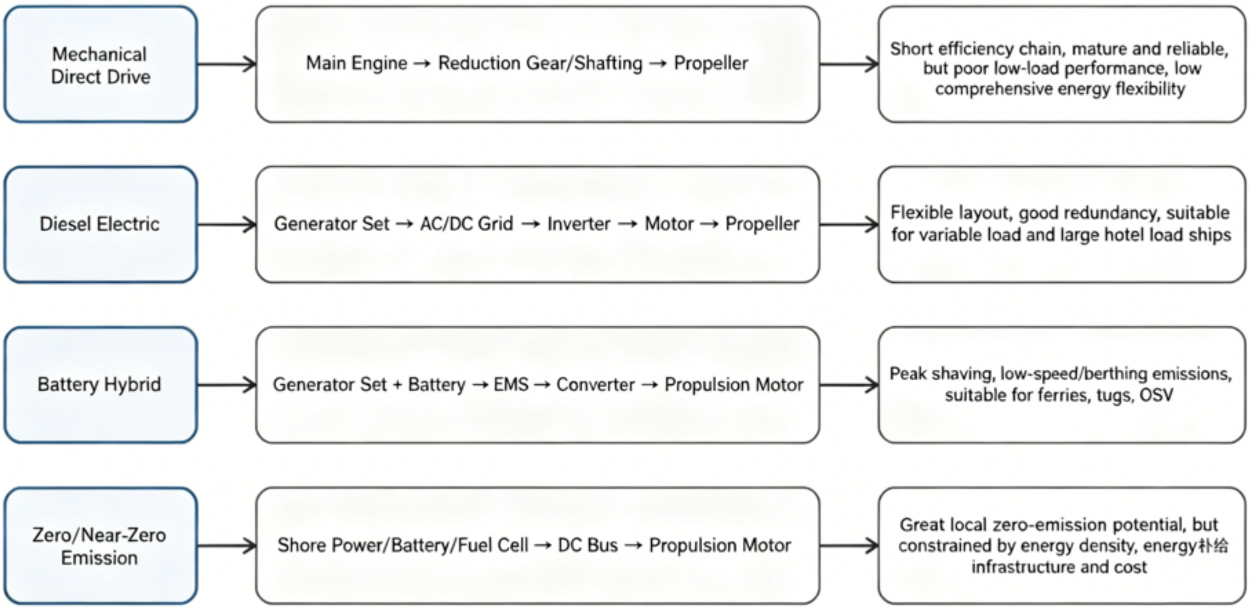

Figure 1. Comparison of Typical Propulsion Topologies

2. Overall System Architecture, Working Mechanism and Ship Power Grid

A typical marine electric propulsion system consists of five parts: energy source side, ship power grid, power electronics, propulsion execution side and control management layer. The energy source side is generally composed of generator sets, energy storage units, fuel cells or shore power interfaces. The ship power grid undertakes power collection, distribution, protection and isolation. Power electronic devices realize voltage and frequency conversion, bidirectional energy flow control and power quality regulation. The propulsion execution side includes propulsion motors, shafting, gearboxes, podded or azimuth thrusters. The control management layer covers propulsion control system, energy management system, monitoring and alarm system as well as ship automation system. Fig.1 illustrates the typical energy flow and information flow relationship of the system.

Table 1. Comparison of Ship Propulsion Schemes

Solution	Typical Energy Chain	Advantages	Limitations	Applicable ship types
Mechanical Direct Drive	Main Engine - Shafting - Propeller	Short link, mature technology, rich maintenance experience	Poor efficiency under low load, weak multi-energy access capability	Ocean-going cargo ships, traditional merchant ships
Diesel-Electric Propulsion	Generator Set - Power Grid - Frequency Converter - Motor	Flexible layout, good redundancy, superior maneuverability	Increased conversion links,high initial investment	Cruise ships, offshore engineering vessels, research vessels
Battery Hybrid	Generator Set + Battery - EMS - Propulsion Motor	Peak shaving and valley filling, zero emission at low speed, fast dynamic response	Complex battery safety and life management	Tugboats, ferries, OSVs, harbour service vessels
Pure Battery	Shore Power/Battery - Inverter - Motor	Zero emission on board, low noise and low maintenance	Limited cruising range, dep endent on charging facilities	Inland waterway ships, short-route ferries, sightseeing vessels
Fuel Cell Hybrid	Hydrogen/Methanol etc. - Fuel Cell + Battery - Motor	Zero/near-zero emission potential, low noise	Restricted by fuel supply and cost, relevant specifications are still evolving.	Demonstration ships, passenger ships, offshore vessels

Under steady sailing conditions, the energy management system determines the number of operating generator sets, load distribution among units, battery charging and discharging power as well as busbar operation modes according to speed commands, propulsion load, hotel load, generator efficiency curves and energy storage status. The propulsion control system adjusts the output frequency, voltage and current of frequency converters based on speed and thrust commands issued by the bridge or dynamic positioning system, so as to enable propulsion motors to generate required torque. In case of sudden load changes, batteries or supercapacitors can rapidly provide power support and prevent frequent and large-scale speed regulation of diesel generator sets. Under low-load operating conditions, partial units can be shut down while energy storage devices sustain short-term loads, effectively reducing fuel consumption and carbon deposition risks at low loads.

When berthing, entering/departing ports or navigating in environmentally sensitive areas, the system can switch to battery-priority or shore power supply mode. For short-route ferries, batteries supply power during navigation and are rapidly recharged via high-power shore power after berthing. For hybrid tugboats, batteries bear power demands during standby, low-speed sailing and transient peak loads, while main engines only engage in high-thrust operations. For cruise ships and research vessels, electric propulsion reduces noise and vibration, improving comfort and measurement environment quality. Accordingly, the operating mechanism of electric propulsion is summarized as multi-energy coordination, dynamic power allocation, variable-speed propulsion control and state-constrained optimization.

The design challenges of electric propulsion systems lie in strong multi-field coupling, diverse operating conditions and numerous constraint limits. Propulsion load is approximately in cubic relation with ship speed, while actual navigation is further affected by wind, wave, current, draft, hull fouling, maneuvering operations and dynamic positioning tasks. The efficiency of generator sets varies greatly with operating load, and the service life of energy storage devices is restricted by charge-discharge rate, ambient temperature and SOC operating range. Frequency converters and propulsion motors are required to satisfy strict requirements on high power density, heat dissipation, electromagnetic compatibility and system redundancy. In addition, marine classification rules mandate that the system shall maintain essential propulsion capacity and safety functions after single-point failure. Therefore, engineering design cannot merely rely on simple superposition of rated power, and systematic optimization shall be carried out based on mission profile, load spectrum, failure modes and life-cycle economic performance.

Ship power grid serves as the framework of electric propulsion systems. Traditional marine power grids are dominated by AC power distribution, featuring mature standards, complete protective equipment and abundant engineering experience. Medium-voltage AC grids are widely applied to high-power cruise ships, LNG carriers and offshore engineering vessels, while low-voltage AC grids are suitable for small and medium-sized ships. A typical AC system consists of diesel generator sets, main switchboards, transformers, propulsion frequency converters, propulsion motors and auxiliary loads. It boasts mature technology and stable equipment supply chains. Nevertheless, when a large number of batteries, fuel cells, DC loads and variable-frequency thrusters are integrated into the system, multiple-stage AC/DC/AC conversion will be involved, which increases equipment volume, power loss and control complexity.

DC power grids connect power generators, energy storage units and propulsion frequency converters via DC busbars, which are particularly suitable for variable-speed generator sets and energy storage systems. Generators are no longer required to maintain a fixed frequency strictly and can adjust rotating speed according to actual loads, thus improving part-load efficiency. Batteries and fuel cells naturally output direct current, enabling more convenient access to the system. Propulsion inverters draw power from DC busbars, eliminating intermediate transformers and rectification links. Marine DC Grid solutions launched by enterprises such as ABB highlight their advantages in equipment weight, space occupation, energy efficiency and multi-energy integration [10]. Relevant academic studies generally confirm that DC power grids possess great application prospects in dynamic positioning vessels, offshore engineering ships and medium-low power hybrid ships, while its technical benefits vary with ship types, load spectra and design constraints.

However, converting an AC busbar into a DC busbar is far from the only change needed for DC power grids. DC short-circuit faults lack natural current zero-crossing points, leading to rapid fault current rise and great difficulties in circuit breaking and selective protection. Massive power electronic interfaces reduce system inertia, and bus voltage stability heavily relies on advanced control strategies. Specialized designs are also required for insulation monitoring, grounding modes, arc flash risks and fire isolation measures. In addition, medium-voltage DC systems still face challenges including immature industry standards, high equipment costs, insufficient classification society certification and limited crew maintenance capabilities. Consequently, there is no absolute superiority among AC, DC and hybrid AC/DC power distribution schemes. The optimal system architecture shall be determined according to ship mission profile, power rating, redundancy requirements and energy allocation configuration.

The Integrated Power System (IPS) further integrates propulsion loads, hotel loads, operational loads, radar and communication loads, as well as future high-energy equipment into a unified marine power platform. For civilian ships, IPS facilitates the integrated optimization of propulsion, air conditioning, cargo handling, deck machinery and shore power systems. For naval vessels, it can also support pulsed loads such as electromagnetic launchers, high-energy lasers and advanced sensors. Given that propulsion loads generally account for a large proportion of the total ship power, electric propulsion stands as the core and most fundamental application scenario of ships equipped with integrated power systems.

3. Key Equipment and Core Technologies

(1) Generator Sets and Prime Movers Diesel generator sets remain the mainstream power source for most electric propulsion ships. They feature mature fuel supply, wide power coverage and sound maintenance support. Electric propulsion enables multiple units to operate in combination according to load demands, keeping single units working within high-efficiency ranges. For engines fueled by LNG, methanol or ammonia, electric propulsion realizes load decoupling and mitigates direct impact of fluctuating propulsion loads on main engines. In the future, ocean-going vessels will unlikely rely purely on batteries. Instead, they will adopt low/zero-carbon fuel main engines equipped with shaft generators, energy storage and auxiliary electric propulsion to boost energy efficiency and meet emission regulations.

(2) Battery Energy Storage System Lithium-ion batteries are the most dominant energy storage form for ship electrification, serving peak shaving, load smoothing, spinning reserve, black start, zero-emission navigation in harbors and short-distance propulsion. Marine battery systems consist of cells, modules, battery clusters, battery management system, thermal management, fire protection, ventilation, insulation monitoring and high-voltage power distribution. Its design takes into account not only capacity and power, but also usable SOC range, cycle life, temperature rise, segmented redundancy, fault isolation and thermal runaway suppression. Compared with automotive batteries, marine batteries have larger capacity, longer operating hours and more enclosed installation spaces. Thermal runaway and toxic gas emission may lead to severe consequences, making industry specifications and risk assessment extremely essential.

(3) Fuel Cell System Proton exchange membrane fuel cells are suitable for applications requiring fast dynamic response and medium-to-low power output. Solid oxide fuel cells feature high efficiency and broad fuel adaptability yet suffer from complex dynamic response and thermal management. Fuel cells are rarely used to bear all transient loads independently; they generally form hybrid systems with batteries, where fuel cells supply steady base loads and batteries cope with peak power and rapid load fluctuations. This operating mode extends fuel cell service life and improves overall system efficiency. Current major constraints involve hydrogen/synthetic fuel supply, storage space, fuel safety, system cost, performance degradation and insufficient bunkering infrastructure at ports.

(4) Power Electronic Converters Propulsion frequency converters act as the speed governors of electric propulsion systems, regulating motor torque and rotational speed by adjusting output voltage, frequency and current. With rising power ratings, marine converters are confronted with challenges such as large current, high heat flux density, harmonic distortion, electromagnetic interference, insulation stress and redundant bypass design. Wide-bandgap devices represented by SiC can increase switching frequency and power density, while their reliability, heat dissipation, cost and maintainability still require sufficient verification under high-power marine operating conditions. For DC power grids, DC/DC converters realize energy storage connection, voltage matching and bidirectional power regulation, which are core components for multi-energy coordinated operation.

(5) Propulsion Motors Marine propulsion motors are required to possess high reliability, high efficiency, strong overload capacity, low noise and vibration as well as convenient maintenance. Common types include asynchronous motors, synchronous motors, permanent magnet

synchronous motors and superconducting motors. Asynchronous motors are structurally robust, cost-effective and free from demagnetization risks. Permanent magnet synchronous motors deliver superior efficiency and power density, yet issues including permanent magnet demagnetization, short-circuit back EMF and high cost need to be addressed. Large synchronous motors are well suited for high-power shaft propulsion. Superconducting motors show great potential in power density but involve complicated cryogenic systems and are still in the stage of specialized research and limited application. Motor selection shall be matched with power grade, speed range, cooling conditions, thruster types and fail-safety requirements.

(6) Thrusters and Hydrodynamic Matching Electric propulsion enables motors to output high torque at low speeds, facilitating variable-speed control of fixed-pitch propellers and matching with highly maneuverable devices such as podded thrusters and azimuth thrusters. Podded electric propulsion devices like ABB Azipod place motors in external pods capable of 360-degree rotation. Public data proves that such designs enhance ship maneuverability and reduce fuel consumption for specific ship types [8]. Nevertheless, podded thrusters impose strict requirements on sealing performance, cooling systems, bearings, maintenance accessibility and underwater impact resistance. Its adoption depends on ship type, shipping route, power level and full-life-cycle cost.

Table 2. Key Components and Design Concerns of Marine Electric Propulsion System

Key Components	Main Functions	Core Design Concerns
Generator sets	Provide base load and continuous power	Efficiency curve, start-stop strategy, redundancy, fuel adaptability
Battery system	Peak shaving, standby power, zero-emission navigation	SOC/SOH, thermal runaway, fire safety, end-of-life capacity
Fuel cell	Low/zero-emission power generation	Fuel storage and transportation, dynamic response, service life, thermal management
Frequency Converter / DC-DC Converter	Voltage and frequency conversion, power regulation	Harmonics, heat dissipation, insulation, EMC, redundancy
Propulsion motor	Output torque to drive thrusters	Efficiency, overload capacity, cooling, noise and vibration, maintenance
EMS	Power distribution and mode management	Optimization objectives, safety constraints, interpretability, data quality
Protection system	Fault detection and isolation	Short circuit, arc flash, earthing, selectivity, black start

4. Energy Management, Control Strategy and Design Evaluation

The energy management system (EMS) acts as the "brain" of hybrid electric ships. Its core objective is to minimize fuel consumption, emissions, equipment aging and operational costs while satisfying propulsion power demand, hotel load demand, safety redundancy requirements and energy storage constraints. A standard EMS is responsible for load forecasting, unit start-stop scheduling, power distribution, battery SOC regulation, shore-to-ship power switching, fault derating and operating mode transition.

For dynamic positioning vessels, EMS needs to strike a balance between propulsion redundancy and rapid dynamic response. For ferries, charge-discharge schedules are formulated according to voyage cycles and shore charging time windows. For tugboats, it enables automatic mode switching among standby status, low-speed cruising and high-thrust working conditions.

Common control strategies are categorized into rule-based control, optimization-based control and intelligent control. Rule-based control executes start-stop and charge-discharge logic via preset SOC thresholds, load levels and navigation modes, featuring high transparency, stable operation and easy classification society approval, yet failing to achieve global optimal performance under complex working conditions. Optimization-based methods include dynamic programming, model predictive control, mixed integer programming and equivalent fuel consumption minimization strategy, which comprehensively take fuel cost, battery lifespan and emission reduction into account but rely on accurate system models and sufficient computing resources. Intelligent control adopts reinforcement learning, neural networks and data-driven prediction to enhance adaptability to complicated operating scenarios, while critical challenges such as interpretability, verification certification and generalization capability under abnormal conditions must be resolved for marine safety-critical applications.

The electric propulsion control layer mainly consists of vector control of propulsion motors, frequency converter protection, current limiting, torque restriction, speed closed-loop regulation, thruster thrust allocation and bridge command processing. For azimuth thrusters and dynamic positioning systems, the control target shifts from single-motor speed regulation to collaborative distribution of thrust magnitude and direction among multiple thrusters. Bidirectional coupling exists between propulsion control and EMS: EMS delivers available power and operating modes, while the propulsion system feeds back actual operating load, power limitation status and fault information. In cases of low battery SOC, abnormal bus voltage or generator failure, smooth power derating is implemented to avoid bus voltage collapse and abrupt propulsion fluctuation.

In terms of research trends, shipboard energy management is evolving from single-vessel offline optimization to integrated collaborative optimization covering shipping routes, ports and onshore power grids. For instance, the optimal battery capacity of all-electric ferries is determined by voyage distance, sailing speed, cargo capacity, berthing duration, charging power and electricity price. The unit start-stop strategy of hybrid ships is further associated with carbon tax, fuel price, maintenance expenditure and port emission regulations. Future EMS will be integrated with weather forecasting, speed optimization, hull fouling assessment, port charging queuing management, carbon emission trading and digital twin technology, extending the optimization scope from equipment performance to overall shipping operational efficiency.

Marine electric propulsion design starts with mission profiles rather than rated power parameters. A complete mission profile covers speed distribution, voyage range, berthing frequency, loading/unloading operation modes, dynamic positioning duration, environmental conditions and safety redundancy level. Propulsion and auxiliary load time sequences are extracted from mission profiles to complete the matching design of generator sets, battery capacity and discharge rate, DC bus voltage grade, converter capacity, motor rated power and thruster configuration. In the absence of actual operational load data, preliminary load spectrum can be established via ship model resistance test data, historical sailing speed, AIS navigation data and empirical coefficients, and further calibrated through sea trials and practical ship operation data.

Comprehensive performance evaluation indicators cover energy consumption, emission level, reliability, maneuverability, safety and economic efficiency. Energy consumption indicators include energy consumption per nautical mile, energy consumption per unit cargo volume, average generator load rate, power conversion chain efficiency and shore power utilization rate. Emission indicators involve CO_2, NO_x, SO_x, particulate matter and full-life-cycle greenhouse gas intensity. Reliability indicators include redundancy level, residual propulsion capacity after single-point failure, mean time between failures and maintenance accessibility. Maneuverability indicators contain low-speed response performance, astern maneuverability, turning radius and dynamic positioning accuracy. Economic indicators cover initial investment cost, fuel expense, battery replacement cost, daily maintenance cost, port service charge, carbon emission cost and residual value.

Battery capacity configuration is a core design issue for hybrid propulsion ships. Insufficient battery capacity leads to inadequate peak load shaving and failure to support zero-emission navigation sections; excessive capacity increases hull weight, occupies cargo space, raises upfront investment and reduces cargo carrying capacity. Engineering design needs to satisfy both energy constraints determined by power demand of specific voyage sections and operating cycles, as well as power constraints restricted by maximum propulsion power, transient power fluctuation and system redundancy demands. Meanwhile, capacity attenuation at the end of battery service life must be fully considered. As specified in classification society standards such as ABS rules, energy storage system dimensioning shall be conducted based on expected performance degradation caused by long-term operation and aging.

Economic benefit analysis should not be limited to fuel cost comparison only. Electric propulsion systems require higher upfront investment involving batteries, converters, propulsion motors, power distribution systems, cooling systems, fire protection systems and control systems, yet they can effectively cut fuel expenditure, routine maintenance cost, port emission penalty and noise & vibration governance cost, as well as improve system redundancy and operational flexibility. For fixed-route vessels, stable low-price shore charging conditions and high annual navigation hours greatly shorten the investment payback period of energy storage systems. For ocean-going vessels, the advantages of electrification are mainly reflected in energy efficiency improvement, carbon emission compliance and adaptability to future alternative fuels. Consequently, full life cycle cost (LCC) assessment and life cycle assessment (LCA) of greenhouse gas emissions serve as the core criteria for scheme comparison and selection.

5. Typical Application Scenarios, Safety Specifications and Engineering Challenges

(1) Ferries and inland waterway shipsCharacterized by short routes, fixed schedules and definite berthing time, ferries are the most typical carriers for all-electric and plug-in hybrid propulsion. Battery capacity can be rationally designed based on single-voyage energy consumption, reserve endurance, charging time window and capacity degradation. Inland ships feature low sailing speed and controllable voyage range, with accessible shore-side energy replenishment facilities, making them suitable for all-electric, battery-swapping and hybrid propulsion modes. Main challenges include high initial investment, insufficient charging infrastructure, excessive battery weight occupying deadweight capacity, as well as battery performance management under extreme low and high temperature conditions.

(2) Harbor tugs and working vesselsTugs suffer severe load fluctuations, involving long standby periods, short-time high-power pushing and frequent start-stop operations. Traditional diesel engines operate at low efficiency with heavy emissions under low-load standby conditions. Hybrid battery systems enable battery-only operation during standby and low-speed cruising, while engines and batteries jointly supply power for high-thrust tasks. Such systems deliver rapid power response, optimize ship maneuverability and eliminate black smoke emissions. Electrification of tugs is of great demonstration value in ports with strict environmental protection requirements.

(3) Offshore engineering vessels, dynamic positioning vessels and research vesselsOffshore engineering vessels mostly operate under dynamic positioning mode, requiring continuous fine

adjustment of multiple thrusters to counteract wind, wave and current disturbances. To meet redundancy requirements, conventional generator sets often run under low load for long hours, resulting in high fuel consumption and emissions. Batteries serve as spinning reserve power and transient power buffer, allowing partial diesel generators to shut down or operate within optimal load range. Research and ocean survey vessels have strict demands on noise and vibration control; electric propulsion effectively reduces underwater noise and optimizes acoustic detection working conditions.

(4) Cruise ships and ro-ro passenger shipsCruise ships carry huge hotel loads, and both propulsion and domestic loads require highly reliable power supply. Diesel-electric propulsion enables generator sets to uniformly supply power for propulsion and daily loads, and pod propulsion improves maneuverability and cabin layout efficiency. With increasingly stringent berthing emission regulations, cruise ships and ro-ro vessels are in urgent need of shore power connection and battery auxiliary power to reduce generator operation during port stay.

(5) Ocean-going cargo shipsContainer ships, bulk carriers and oil tankers feature long voyages, large power demand and high energy consumption. Restricted by current battery energy density, full battery-powered propulsion is impractical for ocean-going vessels. Ship electrification for ocean routes mainly adopts integrated solutions including shaft power generation, waste heat recovery, peak load shaving via energy storage, shore power utilization, wind-assisted propulsion, low/zero-carbon fuel engines and intelligent energy efficiency management. Instead of replacing main engines completely, electric propulsion acts as a coupling platform connecting low-carbon fuels and ship integrated power systems.

Ship electric propulsion systems are safety-critical systems that must comply with international maritime conventions, classification society rules, IEC standards and requirements of flag states. IEC 60092-501:2025 applies to marine electric propulsion installations, covering generators, prime movers and other power sources such as fuel cells and batteries, switchboards, transformers and reactors, semiconductor converters, propulsion motors, excitation systems, control, monitoring and safety systems, cables, busbars as well as pod propulsion devices[4]. It indicates that modern codes have incorporated batteries, fuel cells and power electronic devices into the integral part of electric propulsion systems, rather than regarding them as external auxiliary equipment.

Battery safety is one of the most concerned issues. Lithium-ion batteries may suffer thermal runaway caused by overcharging, overdischarging, internal short circuit, external short circuit, mechanical damage, high temperature, cooling failure or manufacturing defects. Thermal runaway releases flammable and toxic gases, which may spread among battery modules and compartments. Ships feature enclosed spaces, difficult evacuation and prolonged fire fighting duration. Therefore, full considerations shall be taken in the design phase including battery compartment layout, thermal insulation, fire separation, ventilation, gas detection, fire extinguishing medium configuration, explosion venting, smoke exhaust, BMS protection and emergency power cutoff. Reliance on BMS software protection alone is insufficient; hardware fuses, contactors, insulation monitoring devices and independent alarm systems are also essential.

Power electronics and power grid safety are equally critical. Frequency converters may generate harmonics and high dv/dt stress, which impair motor insulation, induce bearing currents and interfere with communication equipment. High-power cables and busbars shall be designed against short-circuit current, thermal stability risks and mechanical fastening issues. DC power grids need to realize fault location, rapid circuit breaking and sectional isolation. Marine electric propulsion vessels shall conduct FMEA, fault tree analysis and blackout recovery analysis to verify that single-point faults will not lead to unacceptable loss of propulsion capacity. Higher requirements are imposed on passenger ships, dynamic positioning vessels and dangerous goods carriers in terms of redundant zoning, independent power supply, fire isolation and independent control systems.

Cybersecurity and software reliability are emerging challenges. With the integration of energy management systems, remote diagnosis, digital twins and shore-based operation & maintenance platforms, electric propulsion systems have evolved from standalone electrical facilities into cyber-physical systems composed of numerous controllers, communication networks and software algorithms. Improper power distribution, abnormal data, communication interruptions and cyber attacks may all impair propulsion performance. Future standards will place greater emphasis on software verification, data integrity, network segmentation, access control and event logging. For researchers, introducing intelligent optimization algorithms while ensuring safety compliance and certification feasibility has become a vital research direction.

First, the conflict between energy density and sailing range remains prominent. Batteries have far lower energy density than liquid fuels. Even taking high motor efficiency and frequent charging on short routes into account, all-electric propulsion is more applicable to short-distance fixed-route ships with low and medium power demand. For ocean-going vessels, using batteries as the main power source will take up substantial weight and space, undermining cargo capacity and economic efficiency. Accordingly, the technical route of new energy vehicles cannot be directly copied to ocean shipping. Instead, integrated solutions combining batteries, fuel cells, low-carbon fuel main engines and wind-assisted propulsion should be adopted in line with actual ship operating characteristics.

Second, supporting infrastructure restricts commercialization progress. All-electric and plug-in hybrid vessels require high-power shore charging facilities, standardized shore power interfaces, sufficient grid capacity, charging safety interlocks and unified billing mechanisms. Fuel cell ships need complete industrial systems for the production, storage, transportation and bunkering of hydrogen, methanol, ammonia and other clean fuels. Port infrastructure construction involves power suppliers, port authorities, ship owners, shipyards and regulatory authorities, resulting in high multi-party coordination costs. Inconsistent energy replenishment standards will further raise operational risks for vessels operating on unfixed routes or across multiple ports.

Thirdly, the complexity of system integration keeps rising. Electric propulsion achieves in-depth coupling of mechanical, thermal, electrical, control and safety systems. Battery thermal management determines service life and operational safety, while harmonic interference from converters deteriorates power grid quality. The hydrodynamic characteristics of thrusters affect motor load conditions, and EMS strategies directly govern fuel consumption and battery aging. Superior performance of individual components cannot guarantee optimal overall system performance, and mismatched interfaces may even lead to efficiency reduction and higher failure risks. Hence, ship design needs to shift from traditional component selection to model-driven systematic engineering design.

Fourthly, standards and verification systems are still evolving rapidly. Although IEC, IMO and classification societies have issued a number of relevant standards and guidelines, emerging technologies including new-type fuels, fuel cells, medium-voltage DC power distribution, large-scale energy storage and intelligent control are still under development, lacking long-term operational data in some application scenarios. The large-scale popularization of new technologies from demonstration projects requires complete procedures covering type approval, risk assessment, sea trial verification, crew training, emergency plan formulation and insurance system improvement. Excessively outdated codes will restrict technological innovation, while overly lenient regulations will bring potential safety hazards. Therefore, technological advancement and standard revision must be promoted in tandem.

Fifthly, full-life-cycle low-carbon performance requires strict assessment. The adoption of batteries or fuel cells on ships does not inherently mean zero-carbon operation. If shore power is sourced from high-carbon power grids, or hydrogen, methanol and ammonia are produced via high-emission routes, the overall emission reduction effect throughout the lifecycle will be limited. IMO is promoting an accounting framework based on the life-cycle greenhouse gas intensity of marine fuels[15]. This indicates that the competitiveness of future electric propulsion solutions depends not only on onboard emissions, but also on the carbon intensity covering the whole process of energy production, transportation, storage and bunkering.

Table 3. Adaptability of Electric Propulsion in Different Ship Types and Scenarios

Ship Type / Application Scenario	Mainstream Power Configuration	Core Adaptation Advantages	Main Constraints and Deficiencies	Electrification Adaptation Level
Ferries & Short-distance Inland Ships	All-electric / Plug-in Hybrid	Fixed routes, convenient shore charging, stable load, easy to realize zero-emission navigation	Battery weight reduces deadweight capacity, poor low-temperature performance, insufficient shore charging facilities	Extremely High
Harbor Tugs	Diesel-Lithium Battery Hybrid	Smooth drastic load fluctuation, reduce idle fuel consumption, improve power response and eliminate black smoke emission	Severe battery attenuation under high-rate working conditions, high cost of high-power system	High
Offshore Engineering & Dynamic Positioning Vessels	Diesel-electric + Energy Storage Auxiliary	Energy storage acts as standby power, optimize unit operating load, cut daily operation energy consumption	Strict redundancy requirement, high safety control difficulty, high investment cost	High
Cruise Ships & Ro-Pax Vessels	Diesel-electric + Battery Auxiliary	Stable power supply for hotel loads, convenient shore power access, low berthing emission	Large total power demand, strict noise & vibration control, high safety standard	Medium-High
Ocean-going Bulk Carriers / Container Ships	Hybrid energy-saving + Peak-shaving energy storage	Realize load shifting and energy saving, meet emission control requirements, reserve low-carbon upgrading space	Limited battery endurance, heavy weight occupation, difficult large-scale full electrification	Medium
Ocean-going Large Cargo Ships	Main engine + Shaft power generation + Auxiliary energy storage	Optimize overall fuel economy, assist peak load regulation, match future clean fuel application	High navigation power demand, restricted by battery energy density	Low-Medium

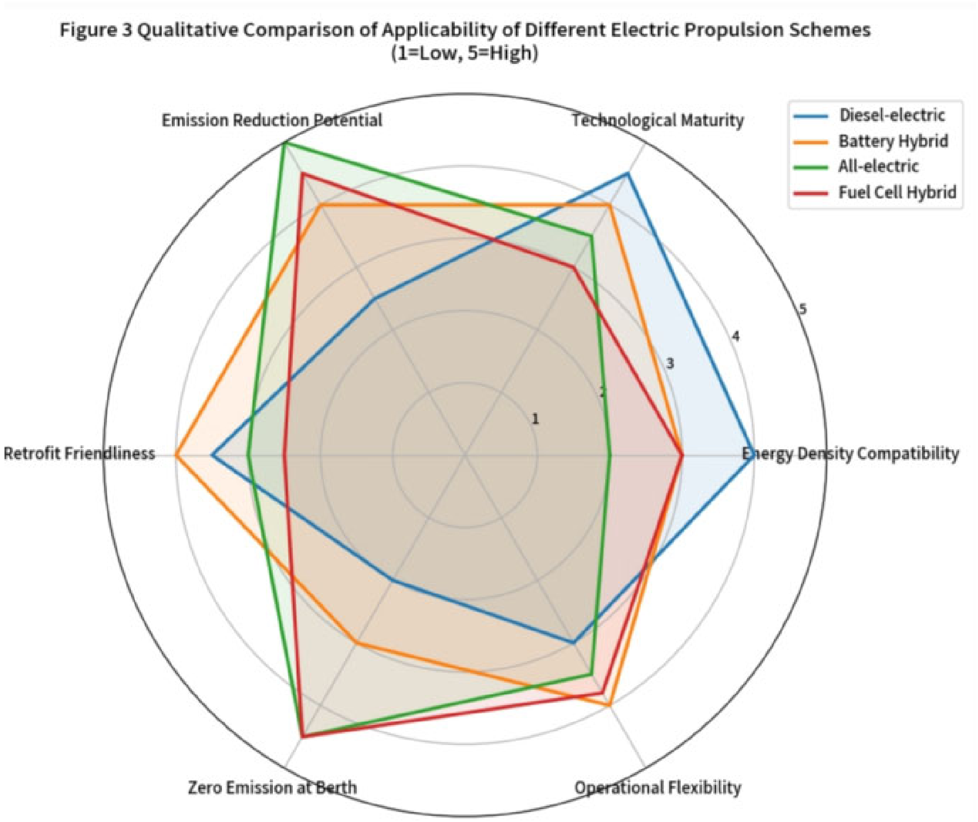

Figure 3. Qualitative Comparison of Electric Propulsion Schemes

Table 4. Challenges and Research Directions for Marine Electric Propulsion

Category	Main Challenges	Key Research Directions
System-level Energy & Power	Low battery energy density limits range; Complex multi-source power scheduling; Lack of accurate load forecasting models.	Whole-voyage energy management optimization; Multi-energy hybrid power system modeling; Data-driven load prediction algorithms.
Safety & Reliability	Battery thermal runaway risks; DC grid fault isolation difficulties; Cyber security threats to EMS; Lack of unified verification standards.	Thermal runaway early warning and suppression; DC protection and black-start technology; Network partition and safety certification; Digital twin-based condition monitoring.
System Integration & Engineering	High system integration complexity; Interface compatibility issues; Unbalanced performance between subsystems.	Model-based system engineering design; Harmonic suppression and EMC design; Battery thermal management and life cycle control.
Standards & Verification	Evolving standards for new technologies; Lack of long-term operational data; Slow certification process.	Development of standards for fuel cells, MV DC, and large-scale energy storage; Digital twin-based virtual verification and sea trial optimization.
Full-life-cycle Carbon & Economy	Inconsistent LCA evaluation methods; High upfront investment vs. unclear return on investment; Unstable carbon policy.	Standardized LCA framework for marine fuels; Whole life cycle cost (LCC) analysis models; Carbon credit trading mechanism design.

6. Development Trends and Conclusions

Trend 1: Development shifts from single electrification to multi-energy hybridization. Short-distance vessels will further advance full battery-powered operation, while medium and long-range ships will widely adopt hybrid configurations combining low/zero-carbon fuels, electric propulsion/auxiliary power, energy storage and shore power access. Batteries are not required to supply all energy demand, yet they play a vital role in peak load shaving, standby power supply, low-speed zero-emission sailing and dynamic power response. Fuel cells are more likely to operate in combination with batteries rather than working independently. Future marine power systems will function as mobile microgrids featured with core capabilities of multi-energy integration and real-time optimal dispatch.

Trend 2: DC power distribution and medium-voltage power electronics will achieve sustained development. With the rising propulsion power and growing access of energy storage systems, medium-voltage DC power distribution, solid-state circuit breakers, modular multilevel converters, wide-bandgap semiconductor devices and intelligent protection technologies will become major research focuses. The core challenges of DC systems lie not in basic power transmission, but in fault protection, stability control, standardized interfaces and maintainability. Breakthroughs in safety-certifiable DC protection and control technologies will accelerate the large-scale application of shipboard DC power grids beyond demonstration projects.

Trend 3: Energy management is evolving from rule-based control towards predictive optimization and data-driven regulation. Vessel operation data, meteorological and sea condition information, port scheduling, electricity prices and carbon prices will all be incorporated into EMS optimization objectives. Model predictive control can balance fuel consumption, battery lifespan and berthing emissions within a finite time horizon. Reinforcement learning enables strategy exploration under complex working conditions, yet it must be integrated with safety constraints, interpretable models and formal verification. Valuable future research focuses not on pursuing overly sophisticated algorithms, but on establishing a safety-oriented optimization framework acceptable to classification societies, seafarers and ship operators.

Trend 4: Digital twin technology and full-life-cycle operation & maintenance will see widespread adoption. Electric propulsion systems, equipped with a large number of sensors and rich control data, are well-suited for state estimation, health management and predictive maintenance. Using digital twin models, it is possible to online estimate battery state of health (SOH), motor temperature rise, converter life consumption and thruster efficiency degradation, thereby guiding speed optimization and maintenance scheduling. For fleet operators, data from multiple vessels can also feed back into new ship design, enabling continuous iteration of battery capacity, unit configuration and EMS strategies.

Trend 5: Coordinated development of standards, ports and energy systems. Marine electric propulsion is no longer an isolated shipborne technology, but an integral part of the port-shipping energy system. Shore power facilities, charging piles, port energy storage, renewable energy resources, hydrogen, ammonia and methanol supply chains, as well as carbon accounting platforms, jointly determine the mainstream technical routes. Discussions on the IMO net-zero emissions framework around 2025 indicate that global shipping emission reduction policies are still evolving dynamically. Relevant mid-term measures include greenhouse gas intensity standards for marine fuels and economic incentive mechanisms. However, as of October 2025, formal deliberation on the amendments to MARPOL Annex VI has been postponed[3]. Accordingly, engineering design shall take both established regulations and uncertain policy risks into account, and maintain open interfaces for various fuels and energy forms.

Marine electric propulsion systems serve as a core supporting technology for the development of green and intelligent ships. It realizes the decoupling of prime movers and thrusters via electrified energy transmission, enabling multi-energy integration, load optimization, redundant configuration and intelligent control. All-electric and battery hybrid propulsion have achieved sound engineering practicability for short-voyage and port operation vessels. For cruise ships, offshore engineering vessels and research vessels, diesel-electric or hybrid electric propulsion can effectively improve maneuverability, comfort and comprehensive energy efficiency. As for mainstream ocean-going ships, electrification will mostly act as an auxiliary platform matching low/zero-carbon fuel systems, rather than completely replacing main engines.

From the perspective of technical system, future research priorities focus on four aspects. Firstly, topology optimization of integrated power systems for multi-energy ships, covering AC/DC hybrid power grids, medium-voltage DC systems and modular interfaces. Secondly, safety, service life and thermal management of energy storage and fuel cells, especially thermal runaway prevention, end-of-life performance evaluation and relevant risk assessment methods. Thirdly, energy management strategies oriented to actual shipping routes and operational data, including certifiable predictive optimization and intelligent control algorithms. Fourthly, evaluation of full-life-cycle carbon emissions and economic benefits, so that technical solutions can achieve high efficiency not only onboard vessels, but also genuine low-carbon performance across energy supply chains, port systems and shipping operation chains.

In general, marine electric propulsion is not a single piece of equipment, but a sophisticated ship energy system engineering. Its performance cannot be merely judged by motor efficiency or battery capacity, but should be evaluated in terms of vessel mission profiles, energy sources, system redundancy, standard compliance and safety, operation and maintenance capacity as well as economic constraints. With the continuous improvement of IMO emission reduction targets, classification society rules, shore power facilities and new fuel supply chains, electric propulsion will evolve from an optional configuration to a basic platform for more ship types, and become a key technical direction for future low-carbon, intelligent and highly reliable vessels.

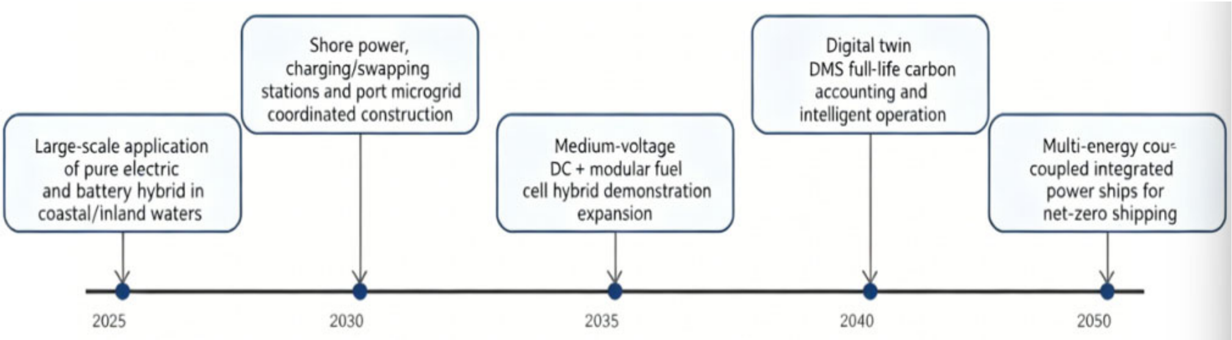

Figure 4. Schematic Diagram of Marine Electric Propulsion Technology Evolution Route

References

[1] International Maritime Organization. Fourth IMO Greenhouse Gas Study 2020. https://www.imo.org/en/ourwork/environment/pages/fourth-imo-greenhouse-gas-study-2020.aspx

[2] International Maritime Organization. 2023 IMO Strategy on Reduction of GHG Emissions from Ships. https://www.imo.org/en/ourwork/environment/pages/2023-imo-strategy-on-reduction-of-ghg-emissions-from-ships.aspx

[3] International Maritime Organization. IMO’s work to cut GHG emissions from ships / IMO Net-Zero Framework updates.

[4] IEC. IEC 60092-501:2025 Electrical installations in ships - Electric propulsion plant.

[5] American Bureau of Shipping. Requirements for Hybrid Electric Power Systems for Marine and Offshore Applications, 2024.

[6] DNV. Battery and hybrid ships.

[7] Kołodziejski M., Michalska-Pożoga I. Battery Energy Storage Systems in Ships’ Hybrid/Electric Propulsion Systems. Energies, 2023.

[8] ABB. Azipod electric propulsion.

[9] Wärtsilä. Electric propulsion system for ships.

[10] ABB. Onboard DC Grid system.

[11] DNV. Maritime Forecast to 2050.

[12] Jabari H. et al. A Review on Propulsion Drive Trains of Electric Ships. Journal of Engineering Materials and Technology/related open PDF, 2025.

[13] Kim K. et al. DC-grid system for ships: a study of benefits and technical considerations. Journal of International Maritime Safety, Environmental Affairs, and Shipping, 2018.

[14] Fan H. et al. Two decades of hydrogen-powered ships (2000-2024). Renewable and Sustainable Energy Reviews, 2025.

[15] International Maritime Organization. IMO framework on lifecycle GHG intensity of marine fuels.