

Review

Progress on Research and Application of Energy and Power Systems for Inland Waterway Vessels: A Case Study of the Yangtze River in China

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Abstract

This study focuses on the power systems of inland waterway vessels in Chinese Yangtze River, systematically outlining the low-carbon technology pathways for different power system types. A comparative analysis is conducted on the technical feasibility, emission reduction potential, and economic viability of LNG, methanol, ammonia, pure electric and hybrid power systems, revealing the bottlenecks hindering the large-scale application of each system. Key findings indicate that: (1) LNG and methanol fuels offer significant short-term emission reductions in internal combustion engine power systems, yet face constraints from methane slip and insufficient green methanol production capacity, respectively; (2) ammonia enables zero-carbon operations but requires breakthroughs in combustion stability and synergistic control of NO_x; (3) electric vessels show high decarbonization potential, but battery energy density limits their range, while PEMFC lifespan constraints and SOFC thermal management deficiencies impede commercialization; (4) hybrid / range-extended power systems, with superior energy efficiency and lower retrofitting costs, serve as transitional solutions for existing vessels, though challenged by inadequate energy management strategies and multi-equipment communication protocol interoperability. A phased transition pathway is proposed: LNG / methanol engines and hybrid systems dominate during 2025–2030; ammonia-powered systems and solid-state batteries scale during 2030–2035; post-2035 operations achieve zero-carbon shipping via green hydrogen / ammonia.

Keywords: inland waterway vessels; energy and power systems; low-carbon fuels; zero-carbon fuels; electric power; hybrid power; range-extended power



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1. Introduction

With the persistent intensification of global warming, reducing greenhouse gas emissions has become an international focus. As the largest global carbon emitter, China sees the transportation sector accounting for over 10% of national carbon emissions. Studies indicate that carbon emissions from Chinese inland waterway shipping reached 32.38 million tons

in 2022 [1]. The existing fleet of inland waterway transport vessels in China approaches 110,000 ships, yet the penetration rate of the clean energy power systems remains below 3% [2]. From 2007 to 2022, CO₂ emissions from inland waterway vessels in the Yangtze River of China increased from 2.418 million tons to 10.801 million tons [3]. To achieve the goal of “carbon neutrality and carbon peak” promoting the transition of inland waterway vessels toward low-energy-consumption and low-emission operation has emerged as a critical pathway to address key constraints on achieving the carbon peak in the transportation sector [4].

At the current stage, the decarbonization transition of inland waterway vessels is primarily achieved through technical approaches including operational management optimization, energy efficiency technology optimization, alternative energy application, and propulsion system modification. Operational management optimization constitutes an effective pathway for decarbonizing inland waterway vessel power systems. Camargo-Díaz et al. [5] systematically investigated economic incentive measures for decarbonizing maritime and inland waterway transport across 16 countries. The results demonstrated that differentiated port fee schemes, as a core operational incentive mechanism, effectively reduce the operating costs of shipowners and promote vessel energy efficiency enhancement by evaluating the environmental index of inbound vessels and providing port fee discounts to low-carbon emission vessels. Tan et al. [6] explored decarbonization pathways for inland waterway container fleets under a carbon cap-and-trade scheme (CCT) by constructing a bi-level programming model. The findings indicated that operational management optimization is an effective approach for achieving emission reduction targets in inland container fleets. Shipping enterprises can achieve a Pareto-optimal balance between economic feasibility and environmental benefits through the synergistic optimization of route deployment strategies and engine fuel technologies. Issa et al. [7] systematically analyzed technological pathways, policy frameworks and operational strategies for decarbonizing the shipping industry. The research showed that decarbonization of inland waterway vessels does not necessitate reliance on disruptive technological breakthroughs. Readily achievable emission reductions of 10–30% can be realized through targeted operational management measures such as slow steaming, regular hull and propeller maintenance, and lightweight operations.

Fuel consumption during vessel manufacturing and operation can be reduced through energy efficiency technology optimization measures such as hull lightweight design and dynamic speed adjustment, thereby lowering carbon emissions. Palomba et al. [8] employed a multi-criteria decision-making method to evaluate the potential carbon reduction advantages of lightweight structures in hull design and operation. The results demonstrated that replacing traditional steel inner shells with renewable aluminum honeycomb sandwich panels achieves an 11% reduction in hull weight. Furthermore, energy consumption during the manufacturing phase decreases by 57% compared to conventional all-steel designs, with a 71% reduction in lifecycle carbon emissions. Wang et al. [9] utilized actual voyage data from a 300,000 DWT bulk carrier. They applied the K-means clustering and K-nearest neighbor (KNN) classification algorithms to segment the route based on sea conditions and investigated the carbon reduction effect of dynamic speed adjustment using a genetic algorithm. The results showed that on the route from St. Louis, Brazil, to the Cape of Good Hope, Africa, optimized operations reduced main fuel oil consumption by 3.38% and lowered CO₂ emissions by 87.64 tons. Both fuel consumption per unit distance and carbon emissions demonstrated significant reductions.

The adoption of alternative energy sources or modifications to power systems represents the ultimate pathway towards achieving zero-carbon emissions from inland waterway vessel power systems. The adoption of clean alternative energy sources or modifications in

power systems represents the ultimate pathway toward achieving zero-carbon emissions from inland waterway vessel propulsion. Currently available alternative energy options for inland vessel power systems mainly include LNG, methanol, ammonia, biodiesel, and liquefied biogas (LBG). LNG holds a dominant position in commercial applications within inland shipping due to its well-established storage and transportation infrastructure and its ability to reduce CO₂ emissions by over 20%. Methanol, particularly green methanol, demonstrates significant emission reduction potential. Its liquid state at ambient temperature enables direct compatibility with existing bunkering infrastructure, considerably lowering retrofit costs. Green methanol can reduce lifecycle carbon emissions by more than 90% compared to conventional fuels. Green ammonia has also attracted widespread attention. Its synthesis relies on renewable energy, and combustion can achieve near-zero carbon emissions. However, the technological maturity of green ammonia remains at the validation stage. Improving combustion efficiency and optimizing power performance are still critical technical challenges that need to be addressed.

Biodiesel and LBG are indeed potential options for decarbonizing inland vessels. According to existing literature, biodiesel is mostly applied in blends with traditional diesel, which can be retrofitted using existing fuel supply systems [10]. It has been piloted in short-distance passenger ships and small cargo vessels, with a life-cycle CO₂ emission reduction rate of 50–80% [11]. LBG has combustion characteristics similar to LNG and can be directly adapted to LNG power systems. Its life-cycle carbon emissions from organic waste anaerobic fermentation are over 90% lower than diesel [12]. However, LBG and biodiesel are derived from organic waste, such as through anaerobic digestion of food waste. Nevertheless, their practical blending ratios are generally limited to $\leq 20\%$ due to constraints in feedstock supply stability and issues related to engine carbon deposition at higher blending ratios, which significantly restricts their substitution potential.

The technical pathways for modifying propulsion systems primarily include pure electric power, hybrid power systems (incorporating regeneration technology), and the direct utilization of renewable energy harvesting technologies such as wind, solar, and tidal energy. Pure battery-powered propulsion systems have demonstrated application value in short-distance inland waterway transport, particularly for intra-port operations and regional short-haul routes. However, the technology is constrained by limited battery energy density, and insufficient range remains a major obstacle to its adoption in medium- and long-distance shipping. Hybrid power systems integrate the advantages of both internal combustion engines and electric propulsion, achieving a balance between emission reduction and operational flexibility. These systems can intelligently switch power modes according to navigation conditions, prioritizing electric propulsion in near-shore areas and environmentally sensitive waters to effectively reduce local emissions while ensuring power availability for long-distance voyages. Regeneration, as an optimization direction for hybrid systems, enables secondary energy utilization through technologies such as braking energy recovery and waste heat recovery from main engines. Among renewable energy harvesting technologies, wind-assisted propulsion and solar photovoltaic systems serve as auxiliary energy technologies that can play a supplementary role in the power systems of inland vessels, though their energy contribution to the main propulsion system is generally less than 15%. Marine energy technologies, including tidal energy, also show potential for application in specific inland waterway segments, though their energy conversion efficiency and device adaptability still require further optimization.

Currently, LNG and methanol represent the most prominent clean alternative fuels for inland waterway vessel propulsion systems. Owing to its mature commercialization, LNG has been widely adopted in thousand-tonnage-class cargo ships operating on medium- and long-distance routes along major waterways such as the Yangtze River and Pearl

River. Methanol has demonstrated significant emission reduction benefits in short-route pilot projects in provinces such as Jiangsu and Hubei, with conversion costs estimated at only 60% of those for LNG-powered vessels. Although the application of ammonia fuel remains relatively limited in inland vessel propulsion systems, its zero-carbon emission characteristics have garnered strong governmental support. Demonstration projects for pure ammonia-fueled vessels have been initiated in regions including Anhui and Shandong. Pure electric propulsion has achieved large-scale application in port service vessels and scenic tour boats, while hybrid-powered ships exhibit notable advantages in complex navigation zones such as the Three Gorges Reservoir area of the Yangtze River.

In contrast, the widespread adoption of other energy sources, such as biodiesel, liquefied biogas, wind, solar, and tidal energy, as well as energy regeneration technologies within hybrid propulsion systems, faces multiple constraints in the context of inland vessels in the Yangtze River Basin. For instance, when the blending ratio of biodiesel exceeds 20%, the rate of carbon deposit accumulation in fuel injectors increases more than threefold. Moreover, the annual collection of waste cooking oil in China amounts to only about 3 million tons, sufficient to meet just 5% of the fuel demand of inland vessels. The production of liquefied biogas relies on agricultural waste, and its economic feasibility requires a collection radius within 50 km; beyond this, transportation costs rise by 50%. Wind-assisted propulsion systems are constrained by vertical clearance limitations under inland bridges, with unit output generally below 20 kW, contributing only 3–5% to the propulsion needs of a 500-ton vessel [13]. Solar photovoltaic panels in the Yangtze region can typically only support auxiliary energy demands such as air conditioning, and entail high initial investment costs [14]. Tidal energy is applicable only in specific segments such as the lower Qiantang River, where single-unit costs exceed RMB 5 million and the investment payback period extends beyond 15 years. As for energy regeneration technologies, the low operating speeds and limited braking opportunities of inland vessels, combined with relatively low main engine power, result in minimal recoverable energy. Additionally, the complex sediment-laden water of the Yangtze River accelerates wear in energy recovery components, leading to a cost-benefit imbalance that hinders broader implementation.

Previous studies have conducted systematic comparisons of the carbon emissions and economic performance of different power systems in inland waterway vessel applications. Yan et al. [15] investigated a typical inland bulk carrier in the Yangtze River. They developed a lifecycle assessment model using the GREET software to calculate the lifecycle carbon emissions of six power systems: diesel, LNG (liquefied natural gas), LNG-battery hybrid, hydrogen, methanol and ammonia. The results indicated that LNG, LNG hybrid and methanol power systems achieve lifecycle carbon emission reductions of 31.5–38.1% compared to diesel. Furthermore, green hydrogen and green ammonia fuels, due to their zero-carbon production, reduce emissions by 78.8% and 91.3%, respectively. Fan et al. [16] conducted a comparative study on the decarbonization potential and economic viability of pure electric and hybrid vessels operating on Chinese inland waterways, employing lifecycle assessment (LCA) and lifecycle cost analysis (LCCA) methodologies. The findings revealed that although pure electric vessels entail higher initial investment, they achieve a 17.78% reduction in total costs over a 30-year operational period through lower fuel costs and carbon tax exemption mechanisms. For LNG-battery hybrid vessels operating under complex high-flow conditions in the upper reaches of the Yangtze River, optimized energy allocation enables a 33.44% reduction in CO₂ emissions, with lifecycle costs decreasing by up to 39.15%. Feng et al. [17] analyzed the decarbonization potential of electric vessels in the inland waterway freight sector using a constructed shipping emission-energy-economic impact assessment model. The results demonstrated that decarbonization of inland waterway vessels can be realized through the electrification of power systems.

When the market share of electric vessels reaches 35%, the cumulative lifecycle carbon emissions from inland freight vessels during the 2022–2050 period could be reduced to 1 billion tons, representing a significant 30.4% reduction compared to the conventional diesel-powered baseline scenario.

Overall, the most promising alternative fuels for inland vessel power systems currently include LNG, methanol, and ammonia. Meanwhile, pure electric and hybrid power systems also demonstrate considerable potential due to their advantages in emission reduction and scenario applicability. Therefore, this paper subsequently focuses on analyzing the application of these energy and power systems in inland shipping.

From the above analysis, it can be known that the current research frameworks on carbon reduction technologies for inland waterway vessels encompass key technical directions including operational management optimization, hull structure optimization, hybrid power system integration, fully electric propulsion technology development and low-carbon/zero-carbon alternative fuel applications [18,19]. However, comprehensive analysis reveals the following limitations in existing research. First, systematic comparative analysis of energy efficiency performance and environmental benefits across different technological pathways remains insufficient. Second, technical applicability and scalability potential of various carbon reduction solutions under specific inland waterway operational scenarios have not yet been comprehensively validated.

In response to the above issues, this study systematically examines cutting-edge advancements in energy and power technologies based on the operational requirements of vessels navigating the Yangtze River. Through horizontal comparison, the differences among various technical solutions in terms of energy efficiency metrics, emission reduction effects and economic viability were revealed. Building upon this foundation, with core focus on compatibility with inland vessel power requirements, we conduct comprehensive evaluations of application value and development prospects for diverse energy supply modes and power systems.

2. Analysis of Energy and Power Forms of Inland Waterway Vessels

2.1. Overview of Energy and Power Forms

2.1.1. Power System Distribution of Vessels in the Yangtze River

The propulsion power of vessels operating in the Yangtze River varies significantly depending on vessel types and operation scenarios. The power distribution characteristics of typical power systems deployed in the Yangtze River are summarized in Table 1.

Table 1. Power system distribution of typical vessels in the Yangtze River.

Vessel Type	Power Range (kW)	Application Scenario	Dominant Power Source
Dry bulk carrier [1]	500–2000	Bulk cargo transportation	Diesel/LNG
Container vessel [1]	500–3000	Container cargo transportation	Diesel/LNG
Passenger ferries [1]	200–1200	Tourism and short-distance passenger transport	Diesel/Hybrid/Electric
Tugs [20]	1500–4000	Assisting large vessel berthing/convoy operations	Diesel
Engineering vessels [21]	800–3000	Waterway dredging and bridge construction	Diesel
Small fishing vessels/patrol crafts [22]	50–200	Fisheries management and maritime surveillance	Diesel/Electric

As evidenced in Table 1, the power systems of typical vessels in the Yangtze River exhibit distinct tiered characteristics. The high-power systems (1500–4000 kW) primarily comprise tugs and engineering vessels deployed for operations in rapid currents or heavy dredging. To meet dual requirements of instantaneous high torque and sustained heavy loads, these vessels predominantly utilize diesel engines fueled by heavy oil, balancing economic viability with combustion stability under high-load conditions. Driven by carbon peak and carbon neutrality goals, innovations integrating energy sources and power configurations are progressively transcending conventional boundaries. Currently, LNG dual-fuel power systems have achieved engineering application in cutter suction dredgers (e.g., Changshi 12), achieving a 60% LNG substitution rate through pilot injection technology while reducing SO_x by 95% at equivalent torque output compared to that of diesel power systems. Some high-power test vessels employ hydrogen-electric hybrid architectures, significantly extending electric operation duration (e.g., test ship of Sany Heavy Industry), while the mass energy density of hydrogen storage systems still constrains full operational coverage.

The medium-power systems (1200–2000 kW) dominated by bulk carriers and container vessels, accounts for over 70% of operational vessels in the Yangtze River. While traditional diesel power systems prevail due to bulk cargo transport economics, the application of alternative fuel power systems such as LNG and methanol is accelerating. For instance, the 10,000-DWT bulk carrier named “Guoneng Changjiang 01” is equipped with 4×620 kW methanol dual-fuel generator sets and 2×500 kWh lithium batteries, with a propulsion power of up to 2000 kW. Through fuel switching, carbon emissions are reduced by 9%.

The low-power systems (50–1200 kW) cover short-distance passenger ferries and small vessels. Fixed routes and lightweight requirements make this segment critical for hybrid and pure-electric technologies. Among these technologies, lithium battery power is the most widely adopted in the low-power segment of marine power systems in Yangtze River. Hydrogen-electric hybrid power systems, with fuel cells supplementing batteries, demonstrate >50% range extension in pilot small official vessels but face scalability barriers due to hydrogen storage density constraints. Additionally, regional navigation environments significantly influence power requirements: vessels in middle/lower reaches leverage gentle currents for energy savings, exhibiting relatively lower power demands, while upstream vessels require 30–40% higher average power due to turbulent flows.

2.1.2. Voyage Distance and Tonnage Distribution of Operating Vessels in the Yangtze River

According to statistics from the Waterborne Transport Research Institute of the Ministry of Transport of the People’s Republic of China, by the end of 2022, the total number of inland vessels in the Yangtze River system was approximately 93,400, with a combined deadweight tonnage of 125 million tons [23]. The average vessel tonnage has increased to 207 tons, marking a 129% growth since 2012, reflecting a trend toward larger and more specialized vessels. The distribution of voyage distance and tonnage of typical vessels operating in the Yangtze River Basin is shown in Table 2. A clear stratification can be observed among vessels categorized by voyage distance. Short-distance vessels (<50 km) are primarily passenger ferries and patrol boats, with an average tonnage of 200–500 tons. Such vessels can undertake 20–30 start-stop cycles per day, with idle energy consumption accounting for up to 30% of total energy use. Medium-distance vessels (50–300 km) are mainly container and bulk carriers, with an average tonnage of 500–2000 tons, requiring a balance between range and operational flexibility. Long-distance vessels are predominantly large bulk carriers and tankers, often sailing continuously for over 48 h, with cruising energy consumption constituting more than 75% of total usage. This differentiated structure

of transportation capacity and energy consumption patterns provides a basis for the precise matching of power systems.

Table 2. Voyage distance and tonnage of vessels in the Yangtze River [1,24].

Voyage Type	Distance Range (km)	Average Tonnage (tons)	Vessel Types	Dominant Power Source
Short	<50	<500	Passenger ferries, patrol boats, small cargo vessels	Diesel/Hybrid/Electric
Medium	50–300	500–2000	Container ships, bulk carriers	Diesel/LNG
Long	>300	>2000	Bulk carriers, tankers	Diesel/LNG

The energy consumption of inland vessel power systems is influenced not only by parameters such as tonnage and voyage distance but also exhibits significant coupling with environmental variables. Affected by the seasonal monsoon in the Yangtze River Basin, downstream vessels in winter can operate at lower power, reducing fuel consumption by 12–15%, whereas upstream vessels in summer require higher power output, increasing fuel consumption by 8–10%. Furthermore, during dry seasons, vessels must reduce speed by 20–30% in shallow segments (e.g., the Jingjiang section) to avoid grounding, leading to a 25% increase in fuel consumption per unit distance. During flood seasons, navigating against strong currents (e.g., downstream of the Three Gorges Dam) requires a 40% increase in power output. Frequent start-stop cycles in foggy or hazy conditions can raise energy consumption by 12–18%.

Under the constraints of the “Carbon peak and carbon neutrality” policy, the potential energy sources for vessels navigating the Yangtze River primarily include LNG, methanol, ammonia and battery power. LNG offers high energy density and a mature application foundation, while its storage and transportation require dedicated infrastructure support. Methanol, as a liquid fuel, provides storage and transportation convenience and can be utilized through modifications to existing fuel systems, but it possesses the physical characteristic of relatively low energy density. Ammonia fuel holds potential for zero-carbon combustion, with current technological focus centered on developing combustion stability and safety protection systems. Battery power systems are suitable for short-distance voyages, but the limitation of energy density leads to a relatively high occupancy rate of cargo space.

From the perspective of power forms, inland waterway marine power systems can be categorized into internal combustion engine (ICE) systems, pure electric power systems, hybrid power systems and range-extended power systems. Traditional ICE systems can be adapted for low-carbon fuels through fuel compatibility improvements. Pure electric power systems rely on high-energy-density battery technology, and their application is constrained by the coverage density of charging infrastructure. Hybrid power systems can be further classified into parallel, series and parallel-series types, each suited to the power distribution demands of vessels operating under different conditions. Range-extended power systems utilize a fuel-powered generation unit coupled with batteries to drive electric motors, thereby extending the cruising range of electric vessels.

Each energy source necessitates matching with an appropriate power architecture for engineering implementation. Fuel-based energy sources rely on energy conversion via ICEs or range extenders, and their emission reduction effectiveness is closely linked to the fuel production pathway. Battery power requires system design considerations based on vessel tonnage and route planning, where the volume and mass of the energy storage unit constitute critical constraint parameters. The implementation of all technological pathways

involves the synergistic development of the energy supply chain, shipbuilding processes and port supporting facilities.

2.2. Comparative Analysis of Internal Combustion Engine Power Systems for Inland Waterway Vessels

As outlined in Section 2.1, diesel engines remain the dominant power system for vessels in the Yangtze River. However, their lifecycle carbon emission intensity is significantly high, making it challenging to meet Chinese strategic goal of deep decarbonization in the transportation sector [25]. To effectively address the decarbonization pressure facing inland waterway shipping, it is imperative to scale up the application of low-carbon/zero-carbon fuels such as LNG, methanol and ammonia in inland vessel propulsion systems. Table 3 provides a detailed comparison of the fundamental power performance parameters for these three clean fuels.

Table 3. Fundamental performance parameters of different fuels in marine ICEs.

Fuel Type	Power Output (kW)	Thermal Efficiency (%)	Energy Density (MJ/kg)
LNG [26,27]	1000–6000 (inland waterway)	40–45	50
Methanol [28]	1000–3690 (inland waterway, MAN L21/31)	35–40	19.9
Ammonia [29,30]	1000–3000 (inland waterway, Wärtsilä 25 Ammonia)	30–35 [31]	18.6

Overall, LNG engines exhibit the highest level of technological maturity. Benefiting from high energy density and relatively high thermal efficiency, LNG engine power output approaches conventional diesel engine levels, making them suitable for long voyages. However, their actual emission reduction effect is somewhat limited due to methane slip. Methanol engines offer a power output range sufficient for the medium-power demands of inland vessels. Yet, significantly lower energy density and thermal efficiency compared to LNG engines result in relatively lower economic efficiency. Although ammonia fuel has zero-carbon emission potential, its low energy density, low thermal efficiency and toxicity pose significant constraints on its application in the power systems of inland waterway vessels in the short term. The following sections will analyze these three types of internal combustion engine (ICE) systems in detail.

2.2.1. LNG Power Systems

LNG serves as a marine fuel, reducing vessel emissions by replacing conventional petroleum fuels. The core emission reduction mechanism lies in the high H/C ratio of methane molecules, reducing CO₂ generation by 20–30% during combustion processes, while virtually eliminating SO_x and PM emissions. Figure 1 illustrates a typical LNG power system. LNG is stored in insulated tanks at a low temperature of −162 °C and delivered via high-pressure and low-pressure supply lines to a vaporizer, converting it to natural gas at ambient temperature. After pressure stabilization, filtration and pressure reduction (to 0.5–1.0 MPa), the gas enters a mixer to be premixed with air, then it enters the engine cylinder. In the cylinder, the mixture is ignited near the end of the compression stroke by a small quantity of diesel fuel (or spark plug/high-pressure direct injection). An electronic control module precisely regulates air–fuel ratio and ignition timing for efficient and clean combustion. Boil-off gas (BOG) is compressed for re-injection or supplemental combustion.

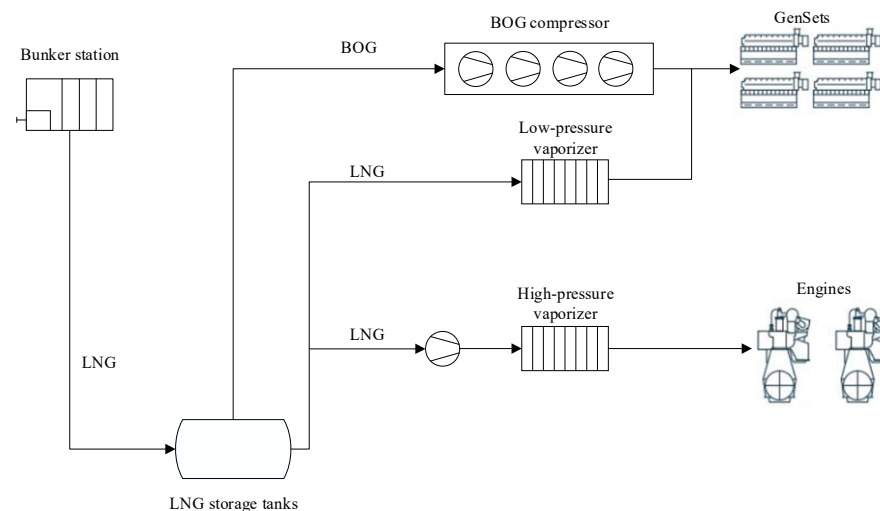


Figure 1. Schematic diagram of the LNG power system.

Regarding combustion modes within the engine, LNG combustion primarily falls into two categories: pilot ignition and spark ignition. Pilot ignition retains the diesel injection system as a highly reactive ignition source, utilizing 5–10% diesel to ignite 90–95% natural gas, and the stratified injection optimizes combustion boundary conditions. This mode is compatible with existing diesel engine architectures, achieves high fuel substitution rates, and is suitable for Otto cycle or Diesel cycle engines. Spark ignition modes mainly comprise three technical types: pre-chamber ignition systems, jet ignition systems and non-prechamber spark ignition system. Pre-chamber ignition systems employ a separate cavity with an integrated spark plug igniting a rich mixture. The resulting high-temperature, high-pressure gas forms high-speed jets through multiple orifices, carrying radicals to ignite the lean mixture in the main combustion chamber. Jet ignition systems utilize a cylinder-head-integrated high-pressure injector to directly generate combustible fuel jets. Turbulent kinetic energy and high-temperature unburned gas from these jets ignite the surrounding mixture, achieving distributed ignition. While non-prechamber spark ignition systems use a spark plug electrode extending into the main chamber to directly ignite a homogeneous premixed charge, completing combustion through flame propagation.

Based on fuel supply paths and injection pressures, LNG engine fuel injection technologies are classified into three categories: port fuel injection, direct injection, and combined injection. Port fuel injection employs single-point or multi-point configurations, with multi-point injection enhancing air/fuel ratio control precision through independently controlled injectors but incurring a 5–10% volumetric efficiency loss. Direct injection is subdivided into low-pressure (5–10 MPa) and high-pressure (30–35 MPa) types, where low-pressure direct injection introduces liquid LNG into the cylinder early in the compression stroke to form a partially premixed mixture requiring pilot diesel ignition or high-energy ignition for stable combustion, while high-pressure direct injection employs near-critical injection near top dead center to achieve near-stoichiometric combustion through stratified mixture organization combined with pilot diesel ignition, enabling thermal efficiency exceeding 50%. Combined injection systems integrate dual supply pathways, with an electronic control unit enabling adaptive regulation based on operating conditions to achieve fuel substitution rates over 90%, though control complexity constrains engineering application.

Economic analysis shows a 35% higher initial investment versus conventional diesels (due to vacuum-insulated tanks and double-walled pipes), with operating costs 30–40% lower than diesel but constrained by gas price volatility and refueling infrastructure gaps—only 3000–5000 DWT vessels demonstrate economic viability [32]. LNG engine emis-

sions exhibit duality. On the one hand, compared with diesel, the use of LNG leads to a significant reduction in the emissions of conventional pollutants (such as $\text{SO}_x/\text{NO}_x/\text{PM}$, etc.). However, the unburned methane slip causes an increase in the actual carbon equivalency, potentially causing higher lifecycle emissions than diesel [33].

Current bottlenecks constraining LNG power system development focus on three aspects: technically, cylinder wall quenching at low speeds increases methane slip to 5%, requiring turbulence-enhanced combustion chambers to optimize flame propagation [34]; in terms of infrastructure, Chinese inland LNG bunkering stations remain insufficient with less than 15% coverage along the Yangtze trunk line; regulatorily, new International Maritime Organization (IMO) regulations requiring the accounting of “Well-to-Wake” emissions, the Greenhouse Gas Fuel Intensity (GFI) to be implemented in 2027 may increase the compliance cost of LNG fuel by 40% [35]. Meanwhile, the IMO 2050 net-zero target subjects LNG to substitution pressure from ammonia, methanol, and hydrogen fuels.

2.2.2. Methanol Power Systems

Methanol has transitioned from trials to commercial application as a low-carbon fuel in inland waterway shipping in the Yangtze River. In July 2024, the vessel “Guoneng Changjiang 01” completed Chinese first green methanol bunkering for inland waterway vessels. By January 2025, the first 50 CCS-classed methanol single-fuel vessels (>2000 kW power) commenced construction on Zhaoqing, Guangdong Province, covering vessel types ranging from 1000 to 10,000 DWT. Compared to conventional heavy fuel oil, green methanol reduces lifecycle CO_2 emissions by 95% in engines. Combined with NO_x reduction technologies like exhaust gas recirculation (EGR), emissions meet IMO Tier III standards [36]. Figure 2 illustrates a marine methanol power system. For methanol engines, liquid methanol is transferred from tanks via a low-pressure pump (8–10 bar) and high-pressure pump (550–600 bar). After treatment through filtration systems and temperature-regulated heat exchangers, the fuel is transported to the engine via leak-proof double-walled piping for injection. Subsequently, combustion is initiated either by micro-pilot diesel compression ignition or forced spark plug ignition. The energy released through combustion drives piston work, ultimately converting to mechanical energy output for the propulsion system.

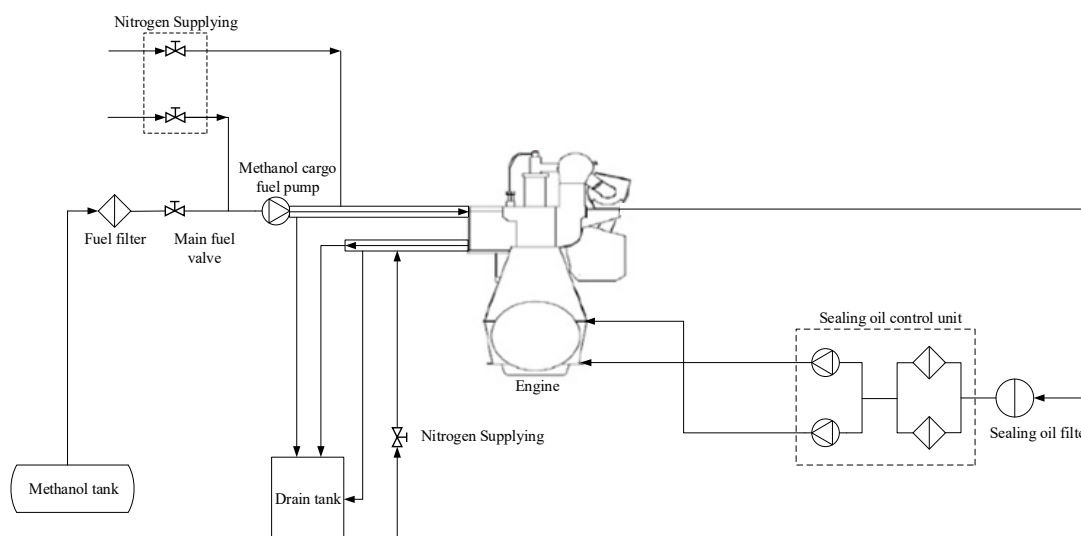


Figure 2. Schematic diagram of the methanol power system.

Based on fuel composition and combustion mechanism differences, marine methanol engines primarily adopt dual-fuel combustion systems or pure methanol combustion

systems. Dual-fuel systems release energy by igniting methanol with micro-pilot diesel through two approaches: High-pressure direct ignition (HPDI) technology injects methanol at an extremely high pressure of over 500 bar via dedicated nozzles directly into cylinders, forming a premixed at the end of the compression stroke, followed by micro-pilot diesel (>800 bar, 5–10% energy share) that ignites the mixture, whereas low-pressure port injection delivers methanol at 4–6 bar through intake manifold injectors, atomizing it into homogeneous mixture with intake air, then igniting via micro-pilot diesel auto-ignition at compression top dead center [37,38]. Pure methanol systems employ forced ignition (spark ignition or pre-chamber jet ignition) for homogeneous mixture combustion, requiring specific combustion chamber optimization to suppress knock and address cold-start challenges.

Current marine methanol engine technology features dual-fuel dominance with accelerating breakthroughs in single-fuel systems. In dual-fuel applications, the ME-LGIM two-stroke engine from MAN ES achieves NO_x reduction through water injection technology, complying with IMO Tier III without Selective Catalytic Reduction (SCR) installation. For four-stroke engines, the 210 mm-bore medium-speed engine developed by CSSC 711 Research Institute employs methanol direct injection, achieving 95% methanol substitution rate, and its integrated high-compact dual-fuel injection systems and intelligent control systems have been deployed on dry bulk carriers in the Yangtze River. Regarding single-fuel technology, CSSC Hudong Heavy Machinery successfully ignited a V8 pure methanol engine suitable for marine and stationary power generation. Additionally, pre-chamber technology enhances power density via distributed ignition, as demonstrated by Ghent University experiments that increased the knock-limited cylinder bore from 150 mm to 200 mm, providing new pathways for high-power single-fuel applications [39].

Marine methanol power systems currently face multiple technological barriers. Technically, the high corrosivity of methanol requires specialized materials instead of conventional aluminum alloys or galvanized steel, which result in the increasing maintenance costs [40]. In addition, the energy density of methanol is only 42% of that of heavy oil, significantly affecting the endurance and cargo capacity of vessels, urgently requiring efficiency-enhancing technologies. From fuel supply and infrastructure perspectives, global green methanol production remains below 500,000 tons annually. Moreover, the carbon reduction benefits throughout the entire life cycle of methanol are highly dependent on the source of raw materials, and the use of grey methanol may even increase carbon emissions [41]. Concurrently, inadequate bunkering infrastructure—lacking standardized interfaces and dedicated bunker vessels—exacerbates supply chain fragility. Regulatory challenges include non-reciprocal European Union certifications (RSB/ISCC) raising cross-border compliance costs, and IMO carbon taxes failing to cover green methanol premiums. All these have affected the large-scale application of methanol in marine power systems.

2.2.3. Ammonia Power Systems

As a zero-carbon energy carrier, ammonia is transitioning from technical demonstration to early commercialization in inland waterway vessels [42]. Represented by the global first pure ammonia-powered demonstration vessel, “Anhui”, which successfully launched in June 2025. Equipped with a 200 kW ammonia-fueled generator, it achieves stable operation at 10 knots. Compared to conventional heavy fuel oil, ammonia engines using green ammonia can achieve lifecycle carbon neutrality. With staged-combustion technology and catalytic cracking for hydrogen enrichment, NO_x emissions fall below IMO Tier III thresholds, however, large-scale adoption still requires optimized DENO_x systems.

Ammonia fuel applications in marine power systems primarily follow three technical pathways: pre-chamber jet ignition for pure ammonia combustion, ammonia-high

reactivity fuel dual-fuel co-combustion and cracking-derived hydrogen synergistic combustion [43,44]. The pre-chamber jet ignition system utilizes hydrogen or diesel ignition in the pre-chamber to generate high-temperature jets, substantially enhancing flame propagation speed through turbulence intensification while utilizing exhaust heat to vaporize liquid ammonia to achieve zero carbon emissions [45,46]. Dual-fuel co-combustion employs ammonia-diesel or ammonia-hydrogen hybrid modes, enhancing reactivity via high-pressure diesel direct injection or premixed hydrogen, coupled with EGR and SCR-AMOX aftertreatment systems for NO_x emissions control. The cracking-derived hydrogen synergistic combustion system catalytically cracks 20–30% liquid ammonia into hydrogen using exhaust heat, with hydrogen igniting the pre-chamber while high-pressure direct ammonia injection occurs in the main chamber, achieving up to 60% N_2O reduction.

Figure 3 illustrates the schematic of a spark-ignition engine system employing hydrogen production via cracking with co-combustion. During system operation, liquid ammonia stored in pressure vessels transfers through pipelines to a primary heat exchanger, where it is preheated and partially vaporized using high-temperature compressed air from turbocharging; subsequently, the preheated ammonia vapor is split into two streams entering a catalytic cracking reactor, partially decomposing into H_2/N_2 mixture, while uncracked ammonia vapor and H_2/N_2 mixture inject into cylinders through separate injection systems, with the turbocharger recycling exhaust energy to compress intake air and improve volumetric efficiency.

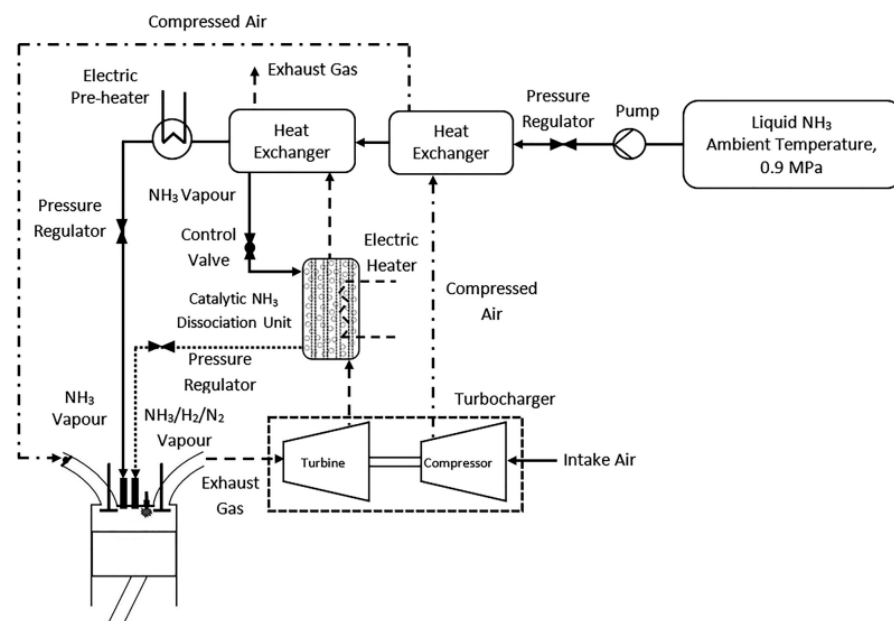


Figure 3. Schematic diagram of the ammonia power system [47].

Ammonia fuel remains non-commercialized for inland vessel propulsion systems, with current technology prioritizing combustion stability enhancement and nitrogen oxide emission suppression [48,49]. For combustion stability, addressing low laminar flame speed and high ignition energy requirements of ammonia, prevailing approaches improve combustion stability through plasma ignition, catalytic cracking for hydrogen production, optimized injection strategies and combustion chamber design [50,51]. Regarding NO_x control, given that ammonia combustion readily generates NO_x and potent greenhouse gas N_2O , current research adopts strategies including staged ammonia supply with premixed combustion, dynamic air/fuel ratio regulation, hydrogen-ammonia co-combustion and low-temperature lean combustion, complemented by flow field optimization to reduce NO_x emissions [52–54].

The applications of ammonia fuel in inland vessel power systems still face multidimensional technical barriers. Firstly, a critical contradiction exists in NO_x emission control during ammonia combustion: ammonia acts as both a NO_x precursor and an SCR reductant, creating a nitrogen paradox. Conventional SCR systems consume additional ammonia for NO_x reduction, while current aftertreatment technologies struggle to achieve simultaneous N₂O and NO_x removal [55]. Secondly, ammonia corrosion toward copper alloys and elastomers necessitates specialized stainless steel for critical engine components, increasing manufacturing costs by over 20%, alongside requiring multi-tiered safety systems to mitigate toxicity risks [56]. Thirdly, the production cost of green ammonia is 2 to 3 times than that of fossil ammonia, and the global bunkering infrastructure severely underdeveloped. Few ports worldwide currently possess supply capabilities of ammonia fuel, indicating significant industry chain immaturity relative to technological validation needs.

2.2.4. Comprehensive Comparison of LNG/Methanol/Ammonia Power Systems

From the perspective of engine power performance, LNG engines deliver power output comparable to conventional diesel engines due to the high calorific value of the fuel and mature technology. Although methanol possesses a lower calorific value, its high-octane number (109 RON) enables high compression ratio combustion. In Homogeneous Charge Compression Ignition (HCCI) mode, the brake thermal efficiency of methanol engines can reach 38% [57]. Ammonia fuel exhibits slow combustion speed, high ignition energy, and significantly lower calorific value and practical combustion efficiency compared to LNG and methanol. Consequently, ammonia engines require optimization of premixing strategies or enhancements in combustion chamber design to improve power density [58].

Economically, LNG offers a price advantage over diesel, and LNG engines exhibit superior thermal efficiency and fuel consumption rates compared to other fuels. However, the associated liquefaction energy consumption and cryogenic storage tank costs contribute to an increased life-cycle cost burden [59]. As the simplest liquid hydrogen carrier, methanol can be integrated with existing powertrains at relatively low retrofit costs. Nevertheless, its lower volatile energy density results in a 20–30% higher consumption rate than LNG. Furthermore, the synthesis of green methanol relies on high-cost electrolytic hydrogen and carbon capture technologies [60]. The production cost of green ammonia is significantly higher than conventional fuels, typically priced at 2–3 times that of diesel per energy unit, necessitating reliance on carbon tax policies to drive near-term commercialization [61].

Regarding emission characteristics, LNG engine can reduce CO₂ emissions by 20–25% compared to diesel engine, yet methane slip partially offsets these benefits [62]. Methanol synthesized from green hydrogen and captured CO₂ can achieve near-zero carbon emissions. Conversely, fossil-based methanol exhibits higher life-cycle carbon emissions than diesel [63]. Ammonia combustion generates no CO₂, and green ammonia production utilizing renewable energy holds potential for deep decarbonization. However, controlling N₂O emissions generated during combustion requires combustion optimization, while NO_x emissions must be mitigated using SCR aftertreatment technologies [64].

Synthetically, LNG power serves as a transitional solution for inland waterway vessels given its technological readiness, pending methane slip mitigation; methanol power excels in liquid fuel storage/logistics and medium-term adaptability but requires policy-driven green methanol scaling; ammonia power holds long-term decarbonization promise yet faces toxicity management, combustion optimization of fuel, and infrastructure gaps—demanding breakthroughs in ammonia/hydrogen co-combustion and safety protocols. Priority should be given to methanol-diesel dual-fuel demonstrations and ammonia combustion optimization to synergize performance and emission goals.

2.3. Analysis of Pure Electric Power Systems for Inland Waterway Vessels

Compared to conventional fossil-fueled vessels, battery-powered vessels demonstrate compelling advantages as a pivotal direction in green shipping technology. Core strengths manifest in three aspects. Environmentally, they eliminate direct exhaust emissions during operation, effectively reducing SO_x , NO_x , PM and greenhouse gases—significantly improving port/coastal air quality and mitigating climate change. Operationally, the electrically driven nature ensures minimal vibration and noise emissions, enhancing crew/passenger comfort while mitigating structural fatigue damage to extend vessel lifespan. In addition, despite higher initial investment, operational expenditures are lower due to the cost advantage of electricity over marine fuels and reduced maintenance from simplified powertrain architecture [65]. Current marine battery technologies comprise two primary categories: storage batteries and fuel cells. Subsequent sections analyze their operational principles, application characteristics, development status and technical challenges.

2.3.1. Battery Power System

In marine battery power systems, the battery pack serves as the core energy storage unit, storing electrical energy supplied by shore power infrastructure or an onboard generator set. During vessel operation, the battery pack discharges power through the Energy Management and Control System (EMCS), which regulates and delivers energy to the main propulsion motor. The propulsion motor converts electrical energy into mechanical energy, which drives the propeller rotation via the transmission system to achieve vessel propulsion.

Commonly used batteries in inland vessels primarily include lead-acid batteries and lithium-ion batteries. Lead-acid batteries currently represent the mainstream choice, offering a low initial capital cost but a high life cycle cost. Primary lithium-ion battery types employed are lithium iron phosphate (LFP) and ternary lithium batteries. LFP batteries exhibit balanced performance, low cost and long service life, demonstrating high compatibility with electric vessels in China. They are predominantly utilized in ferries and sightseeing boats operating on fixed routes. Ternary lithium batteries utilize nickel-cobalt-manganese (NCM) or nickel-cobalt-aluminum (NCA) cathode materials, offering significantly higher power density and superior low-temperature performance, making them suitable for long-range cargo vessels. As a next-generation technology, solid-state batteries possess core advantages including enhanced safety, high energy density and broad operating temperature range, substantially improving vessel environmental performance and reliability. Compared to traditional lithium-ion batteries, solid-state batteries employ non-flammable solid electrolytes, eliminating thermal runaway risks. The modular design of solid-state batteries enables compact integration, particularly applicable to scenarios demanding stringent space and safety requirements such as luxury yachts. Table 4 compares key parameters of marine batteries.

Overall, lead-acid batteries maintain dominance in power systems for coastal patrol boats, small passenger vessels and yachts due to mature production processes and significant cost advantages. However, inherent limitations including low energy density, severe performance degradation at low temperatures, and inadequate recycling systems make them inadequate for main propulsion in large vessels. In contrast, LFP batteries are becoming mainstream for newly built electric ships owing to superior safety and excellent cycle life. However, the limited energy density of LFP constrains the range of large vessels, and thermal runaway risks persist. Although ternary lithium batteries offer relatively higher energy density, significant safety concerns stemming from poor thermal stability and flammable electrolytes severely restrict their marine power applications, currently limited to small experimental vessels. Solid-state batteries—utilizing sulfide/oxide

solid electrolytes—demonstrate potential in safety enhancement, high energy density and wide-temperature adaptability. However, development remains constrained by low ionic conductivity at solid-solid interfaces, complex manufacturing processes, and high costs, keeping them in the demonstration phase.

Table 4. Comparison of key parameters of marine storage batteries.

Battery Type	Energy Density (Wh/kg)	Power Density (W/kg)	Energy Efficiency (%)	Response Time	Cycle Life (Cycle)
Lead-acid batteries [66]	30–50	75–300	80–90	ms	2000–4000
Lithium iron phosphate batteries [67]	90–140	1500–2500	85–95	ms	4000–6000
Ternary lithium batteries [68]	200–250	1200–3000	85–95	ms	2000–3000
Solid-state Batteries [69]	300–500	>500	85–88	ms	>2000

2.3.2. Fuel Cell Power Systems

Fuel cells constitute efficient energy conversion devices comprising an anode, cathode, and electrolyte, transforming chemical energy from fuel into electricity through electrochemical reactions. This technology offers core advantages of zero emissions, low noise and extended endurance potential, recognized by the International Energy Agency (IEA) as a critical pathway toward carbon neutrality. Figure 4 illustrates the basic principle of hydrogen fuel cells: at the anode, hydrogen undergoes oxidation via catalysis, dissociating into protons (H^+) and electrons. Electrons flow through an external circuit, generating electric current to power loads, while protons migrate through the proton exchange membrane (PEM) to the cathode. At the cathode, oxygen combines with electrons returning from the external circuit and protons migrated from the anode, producing water and releasing heat.

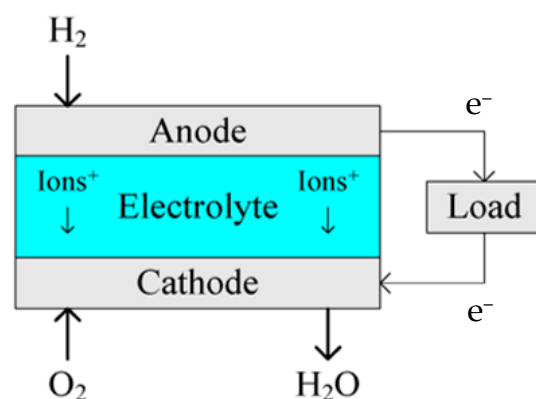


Figure 4. Schematic diagram of hydrogen fuel cells [70].

Based on electrolyte variations, mainstream fuel cells primarily include: proton exchange membrane fuel cells (PEMFC), solid oxide fuel cells (SOFC), molten carbonate fuel cells (MCFC), alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC) and direct methanol fuel cells (DMFC). PEMFC feature fluorinated proton exchange membranes, delivering high power density and rapid start-up. However, their reliance on platinum catalysts results in high costs, and they exhibit sensitivity to CO. SOFC employ solid ceramic electrolytes, achieving >60% energy conversion efficiency with exceptional fuel flexibility. MCFC utilize molten lithium-potassium carbonate electrolytes for direct natural

gas reformat use, however, severe high-temperature corrosion and slow start-up limit them to stationary power plants, precluding mobile applications. AFC with potassium hydroxide electrolytes exceed 60% efficiency and accommodate ammonia-cracked hydrogen but require CO₂ isolation—recently implemented in Norwegian zero-emission cargo ships via green ammonia integration. PAFC support natural gas reforming with 80% cogeneration efficiency using concentrated phosphoric acid electrolytes, yet platinum costs and limited lifespan restrict deployment to marine auxiliary or land-based systems. DMFC directly use liquid methanol, simplifying storage but suffer from low energy density and methanol crossover issues, making them suitable primarily for small portable devices. Key parameters of different fuel cell types are compared in Table 5.

Table 5. Comparison of key parameters of fuel cells.

Battery Type	Energy Density (kWh/kg)	Power Density (kW/m ³)	Energy Efficiency (%)	Fuel Type	Start-Up Time	Theoretical Lifespan (h)
PEMFC [71]	6.1–33	3.8–6.5	50–70	Hydrogen	Seconds–minutes	5000–10,000
SOFC [72]	25–40	0.1–1.5	60–65	LNG/Methanol/ Hydrogen	Hours	8000–90,000
MCFC [73]	13.9	1.5–2.6	45–55	LNG/Methanol/ Hydrogen	Hours	~20,000
AFC [73]	33	~1	60–70	Hydrogen	Minutes	5000–8000
PAFC [74]	33	0.8–1.9	55	Hydrogen	Hours	15,000–40,000
DMFC [75]		~0.6	20–30	Methanol	Seconds–minutes	>20,000

Fuel cells surpass conventional lithium batteries in theoretical energy density, offering inherent advantages for long-range inland waterway shipping. Global marine fuel cell systems are advancing beyond demonstration phases. The hydrogen fuel cell container vessel of “Oriental Hydrogen Port” in Jiaxing, Zhejiang Province, China, adopts a PEMFC–lithium battery hybrid power system, with a range of 380 km and a refueling time of only 10 to 15 min, which is close to the efficiency of traditional fuel. PEMFC and SOFC demonstrate the greatest marine potential. PEMFC dominate short-haul applications through rapid start-up, high power density, and modularity, reducing daily CO₂ by ~4.9 tons with <5% voltage fluctuation during surge events [76]. However, corrosion susceptibility of catalysts and membranes limits stack longevity below the 20,000-h threshold required for 25-year vessel service. In addition, high green hydrogen costs, frequent membrane replacement and ultrapure hydrogen requirements elevate lifecycle expenses. SOFC offer fuel flexibility and superior energy density for mid-long range decarbonization. Recent advances integrate carbon capture (e.g., HD KSOE-DNV’s PSA technology improving efficiency by 40%), though still land-tested [77]. High-temperature operation environment also complicates marine thermal management, precluding near-term commercialization.

Over all, current high system costs favor near-term fuel cell/storage battery or fuel cell/supercapacitor hybrids to balance power and range. Long-term, next-generation high-temperature PEMFC (HT-PEMFC) compatible with methanol/ammonia, declining green hydrogen costs, and expanded refueling infrastructure may establish hydrogen fuel cells as core solutions for zero-carbon inland shipping [78].

2.4. Analysis of Hybrid Power Systems for Inland Waterway Vessels

Hybrid power systems integrate the advantages of both internal combustion and electric propulsion, representing a novel marine power configuration. Based on power

coupling mechanisms, inland vessel hybrid power systems are categorized into series, parallel, and series-parallel types.

In series hybrid power systems (Figure 5), two electric machines serve as propulsion motor and generator respectively. The engine-generator set and battery supply the vessel's electrical grid, powering the propulsion motor to drive the propeller. The system operates in battery-only, generator-only, or combined modes. With only the electric motor providing propulsion while the engine operates independently at optimal efficiency, this configuration avoids load fluctuations but incurs 10–15% secondary energy losses.

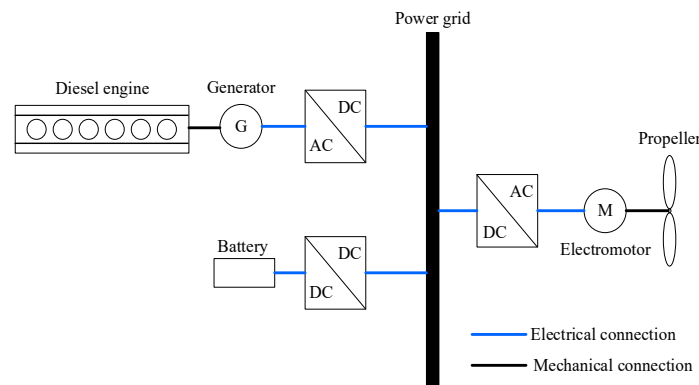


Figure 5. Schematic diagram of the series hybrid power system.

Parallel hybrid power systems (Figure 6) employ mechanical coupling for coordinated engine-motor propulsion. The engine and motor can operate independently or jointly to drive the propeller, with surplus engine power also enabling regenerative generation. Primarily used in medium-range cargo vessels, this design achieves high transmission efficiency but requires sophisticated energy management strategies (EMS).

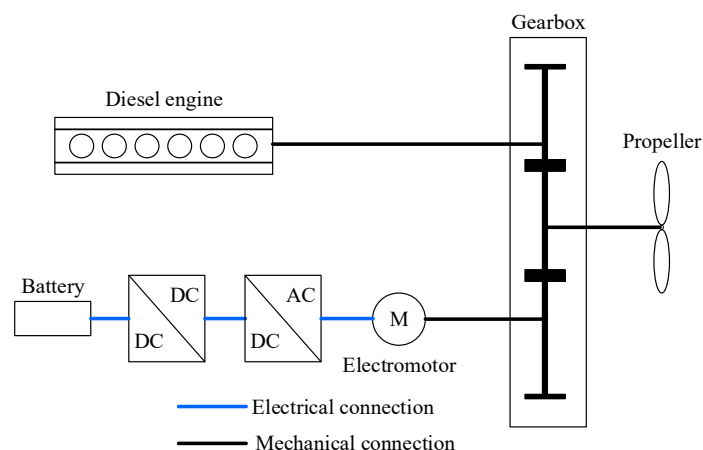


Figure 6. Schematic diagram of the parallel hybrid power system.

Series-parallel hybrid power systems (Figure 7) combine structural features of both configurations. Clutch engagement/disengagement enables mode-switching between series and parallel operation. This architecture integrates the generator set from series systems with the direct-drive capability of parallel systems, offering operational flexibility at the cost of increased structural complexity, advanced EMS requirements, and elevated costs. Table 6 compares key characteristics of these hybrid power systems.

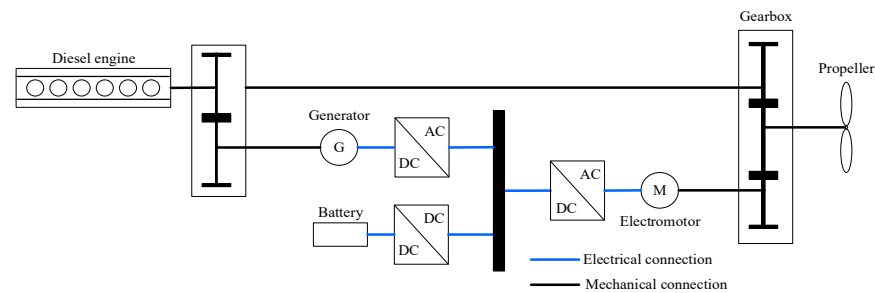


Figure 7. Schematic diagram of series-parallel hybrid power system.

Table 6. Comparison of advantages and disadvantages of hybrid power systems.

System Type	Series Configuration	Parallel Configuration	Series-Parallel Configuration
Architecture	ICE drives only the generator; stored electricity in the battery powers the motor to drive the propulsor	ICE and motor independently or jointly drive the propulsion shaft via a direct power path	Combines series and parallel architectures, with dynamic power distribution via planetary gear
Advantages	a. ICE runs steadily in the high-efficiency range b. Simple structure and precise control c. High technical maturity	a. High overall energy efficiency b. Reduces electric propulsion capacity needs c. Significant efficiency in high-speed cruising	a. High propulsion power b. Flexible adaptation to multiple working conditions c. High energy recovery efficiency
Disadvantages	a. Secondary energy conversion incurs efficiency losses b. High-power generators and propulsion motors are required to increase initial investment	a. Complex power coordination control b. Short pure electric range c. Complex mechanical structure	a. High manufacturing cost b. Difficult to maintain c. High energy loss
Scenarios	Short-distance, high-frequency transportation	Inland medium-range cargo transport	Long routes with complex conditions

Marine hybrid power systems are transitioning from demonstration to commercial scale, with parallel development of diesel-electric/energy storage, fuel cell/energy storage and renewable integration technologies [79]. In diesel-electric systems, the Norwegian offshore engineering vessel “Viking Princess” achieves 30% fuel savings and 13–18% annual CO₂ reduction through LNG engine-storage battery synergy. Fuel cell hybrid power system show promise in research/passenger vessels. For instance, Chinese “Tongji” scientific research vessel employs DC busbars with LFP batteries for 8% energy reduction, while the 1.5 MW-class LNG/hydrogen hybrid engine developed by Hyundai Heavy Industries of South Korea has been certified by DNV and plans to achieve pure hydrogen drive in 2025. For renewables, the solar-assisted inland vessel “Blue Marlin” integrates 192 PV panels directly driving high-voltage propulsion, generating 37,500 kWh annually.

Critical technical barriers persist in engineering applications. Firstly, energy management strategies (EMS) lack real-time adaptability; rule-based controls exhibit up to 30% energy deviation under variable conditions. Though global optimization algorithms (e.g., model predictive control, Pontryagin minimum principle) improve efficiency, computational complexity exceeds embedded systems’ millisecond-level decision capacity [80,81]. Secondly, incompatible communication protocols across multi-vendor equipment (engines, motors, storage) hinder control parameter synchronization. Third, lagging regulatory frameworks, such as IEC 80005-1 lacking hydrogen/ammonia bunkering standards, risk

port supply incompatibility. Finally, inadequate system intelligence and reliability stem from insufficient multi-source data fusion and cascading faults. Despite promising simulations, smart algorithms face deployment challenges including sparse real-world data and hardware incompatibility [82,83].

2.5. Analysis of Range-Extended Power Systems for Inland Waterway Vessels

Range-extended power systems are fundamentally series hybrids with an internal combustion engine as a dedicated range extender and batteries as the primary drive unit. This “battery-dominant, engine-assisted” architecture extends pure-electric vessel range while retaining electric propulsion’s environmental benefits. Key components include power battery packs, drive motors, range extenders, which can be seen from Figure 8.

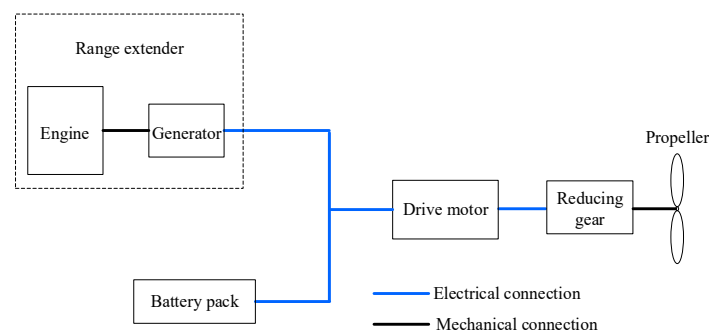


Figure 8. Schematic diagram of range-extended power system.

In pure-electric mode, battery packs power the propulsion motor to drive the propeller, achieving zero-emission, low-noise operation. When battery charge drops below a set threshold, the range extender activates, generating electricity through fuel combustion. This powers the motor and recharges batteries, extending range. The control system monitors operational parameters and intelligently manages range extender activation, implementing peak-shaving/valley-filling energy scheduling to maintain the engine in its optimal efficiency range. This avoids frequent start-stop energy penalties, ensuring efficient operation.

Range extender engines prioritize constant high-efficiency generation, favoring high-compression-ratio, low-emission designs. Unlike hybrid systems, power design focuses on steady-state operation to maximize thermal efficiency, reducing fuel consumption and emissions [84]. Beyond LNG/methanol dual-fuel engines, methanol-to-hydrogen reformers are gaining traction. German Freudenberg HT-PEMFC system exemplifies this approach: integrated with low-temperature tanks and catalytic reactors, it enables zero-carbon navigation via methanol-cracked hydrogen.

Range-extended systems demonstrate multidimensional advantages in inland waterway vessels. For efficiency and emissions control, constant-power generation maintains the engine in its optimal thermal efficiency range, improving overall efficiency by 20–30% compared to mechanical propulsion. Pure-electric operation extends zero-emission navigation in ports and ecologically sensitive waters. Regarding range and operations, the architecture extends cruising range to 3–5 times that of pure-electric mode. Combined with battery swapping and shore fast-charging, it enhances vessel operational continuity and port turnaround efficiency. Economically, despite 20–30% higher initial investment, fuel costs are reduced by more than 40%, while simplified electric drive structures decrease lifecycle maintenance costs by 25–35%.

The application of range-extended propulsion systems in inland waterway vessels still presents a series of challenges. Firstly, although the peak power generation efficiency of diesel range extenders is high, inherent energy conversion losses

(engine→generator→battery→motor) reduce the well-to-wheel efficiency of diesel range extenders to around 35%, which is lower than that of direct mechanical propulsion. Moreover, critical components including dedicated high-speed generators and high-torque marine motors lack mature domestic supply chains, with key materials and manufacturing processes (e.g., high-performance permanent magnets and precision motor windings) lagging international standards. Additionally, certification framework incompatibilities, inadequate adaptability of energy management strategies, and insufficient real-world data for intelligent algorithm training remain unresolved barriers shared with hybrid systems.

3. Analysis of Low-Carbon Transition Strategies and Application Progress for Inland Waterway Vessel Energy and Power Systems

3.1. Low-Carbon Transition Strategy for Inland Vessel Power Systems Based on Voyage Distance

Building upon the operational characteristics of vessels in the Yangtze River Basin by voyage distance (Table 2) and considering the technological maturity, energy-saving potential, and emission reduction performance of various power systems discussed in Sections 2.2–2.5, this section proposes power system selection strategies tailored to different voyage ranges. The aim is to achieve synergistic optimization of energy efficiency and emission reduction from the perspectives of technical principles, performance parameters, and system compatibility.

For short-distance vessels operating below 50 km, a high-rate LFP battery pack combined with a permanent magnet synchronous motor propulsion system is recommended. An intelligent battery management system enables dynamic charge-discharge control [85]. This system significantly reduces idle losses, which account for up to 30% of energy consumption in short-distance voyages, and offers zero emissions, making it suitable for environmentally sensitive areas such as ports and riverside urban zones. With supporting fast-charging infrastructure at ports, it can meet a daily range of 80–100 km. For operational profiles involving 20–30 start-stop cycles per day, a model predictive control-based energy management strategy reduces peak power response time to 0.5–1 s, cutting energy loss by 25% compared to conventional diesel engines [86]. Trial data from electric cargo ships in Nanjing Port show that this system reduces operating costs by RMB 0.35 per ton-kilometer and lifecycle carbon emissions by 92% compared to diesel vessels.

For medium-distance voyages ranging from 50 to 300 km, a hybrid architecture integrating methanol and lithium battery packs is proposed. A multi-energy controller enables operational switching between “electric mode at low speeds and methanol mode at high speeds” [87]. Green methanol can reduce CO₂ emissions by up to 95% over its lifecycle, with nearly zero emissions of sulfur oxides and particulate matter. The Wärtsilä 32 methanol engine, with a thermal efficiency of approximately 45–48%, remains highly efficient (around 40%) even at 50% load, accommodating the frequent load variations typical of medium-distance voyages. The lithium battery pack provides power compensation during start-up, berthing, and acceleration, increasing the proportion of time the engine operates within its high-efficiency range. A particle swarm optimization-based multi-level energy management strategy can reduce fuel consumption by 15–20%. To mitigate fuel consumption fluctuations caused by seasonal monsoon effects, an adaptive speed algorithm dynamically adjusts methanol injection, limiting energy deviation per voyage to within 5% [88].

For long-distance inland vessels, a technically mature LNG-battery hybrid power system is recommended. This approach leverages globally verified real-world operational experience to ensure long endurance while achieving significant carbon reduction, avoiding technical risks associated with new alternative fuels lacking practical operational data [89]. COSCO Shipping Group’s “Yuan Haikou”, scheduled for delivery in 2025, integrates an

energy storage system with LNG propulsion, reducing energy consumption by 20% and CO₂ emissions by 24% compared to conventional diesel vessels. The Wärtsilä 46TS-DF dual-fuel engine, equipped with NextDF technology, limits methane slip to 1.1–1.4% and reduces lifecycle carbon emissions by 25–30% compared to diesel engines. An auxiliary LFP battery pack forms a synergistic “LNG for main power + battery for peak shaving” architecture. A shaft generator charges the battery during cruising, while the battery takes over in congested segments such as the Three Gorges ship locks, reducing idle energy loss. During high-power demand operations such as upstream navigation, the battery provides instant power support, preventing frequent engine start-stops and increasing high-efficiency operation time.

3.2. Forecast of Application Progress for Inland Vessel Energy and Power Systems

Conventional ICEs currently dominate inland vessel propulsion, yet increasingly stringent emission regulations are driving their transition toward low-carbon fuels. Methanol and ammonia ICEs demonstrate strong technical compatibility through catalytic combustion and energy density advantages. Pure electric propulsion remains economically viable only for short-range fixed routes due to battery energy density constraints; its large-scale adoption awaits solid-state battery breakthroughs and battery-swapping infrastructure. Hybrid systems (including range-extended configurations) serve as transitional solutions for retrofitting existing vessels, offering low modification costs and energy optimization. Despite zero-carbon potential, hydrogen and ammonia face storage/transport costs and combustion stability challenges, limiting near-term application to pilot projects [90–92]. Based on the content Sections 2.1–2.5, Table 7 summarizes adoption barriers and projected timelines for different power systems.

Table 7. Technology bottlenecks and breakthrough pathways for low-carbon/zero-carbon alternative power systems in inland waterway vessels.

Power System Type	Fuel Type/Battery Type	Major Bottlenecks	Solution Pathways	Expected Breakthrough Timeline
ICEs	LNG	a. High methane slip rate in existing engines b. Inadequate bunkering station coverage c. Increasingly stringent emission regulations	a. Wärtsilä’s NextDF technology reduces methane slip to 1.1% at 25% load via turbulence enhancement b. Expansion of LNG bunkering network c. Adoption of bio-LNG combined with LNG-ammonia dual-fuel retrofits	a. Commercial delivery of NextDF-equipped engines in 2025 b. 45 bunkering stations planned along Yangtze River trunk line by 2025; projected increase to 60 by 2027 [93] c. Technological iteration expected by 2030
	Methanol	a. Low engine efficiency b. Safety and storage/transportation challenges c. Insufficient fuel supply infrastructure	a. Application of variable compression ratio (VCR) technology b. Implementation of advanced tank technologies c. Scaling green methanol production and bunkering networks	a. VCR technology adoption is expected to reach 30% in newbuild methanol-powered vessels by 2030 b. Sandwich panel tank technology received Lloyd’s Register approval in principle adoption rate is expected to exceed 50% post-2027 IMO regulatory enforcement [94] c. Global green methanol production projected at 37.1 million tonnes annually by 2030 [95]
	Ammonia	a. Combustion instability under low-temperature and high-pressure conditions b. NO _x emission control c. Engine material corrosion protection d. Insufficient fuel supply infrastructure	a. Prechamber ignition/plasma-assisted ignition b. Catalytic system technological breakthroughs c. Application of marine-grade anti-ammonia coatings d. Scaling ammonia production and bunkering networks	a. First ammonia engines (e.g., WinGD) is expected to be delivered in 2025; plasma ignition is expected to reach marine demonstration phase by 2030 [96] b. The N ₂ O catalytic reactor developed by Hitachi Shipbuilding is expected to be installed on an ammonia-fueled ship in 2026, aiming at >90% N ₂ O emission reduction c. Marine-grade anti-ammonia coatings expected to complete 5000-h full-scale validation by 2027 [97] d. The global first ammonia bunkering vessel is expected to be delivered in 2027; Green ammonia supply chain maturity with cost parity to conventional fuels projected post-2035

Table 7. *Cont.*

Power System Type	Fuel Type/Battery Type	Major Bottlenecks	Solution Pathways	Expected Breakthrough Timeline
Pure electric power	Storage batteries	Solid-state batteries remain in demonstration phase without mass production	Suppress electrode-electrolyte interdiffusion; develop composite electrolytes	CATL/BYD are expected to achieve small-batch production by 2027; electrolyte costs are expected to decrease significantly by 2035, enabling full commercialization for inland waterway hybrid power vessels
	Fuel cells	a. Short PEMFC lifespan b. SOFC high-temperature operation requires complex thermal management c. High green hydrogen costs	a. Develop stable catalysts/supports; implement intelligent lifespan prediction and adaptive control b. Integrate waste heat recovery; adopt phase-change material insulation to reduce cabin temperature rise c. Improve alkaline electrolyzer efficiency; advance green hydrogen commercialization	a. PEMFC lifespan is expected to reach 20,000 h by 2030 leveraging European projects b. Samsung Heavy Industries' 174,000-ton LNG carrier with MW-scale SOFC hybrid system is expected to be delivered in 2027; full maturity is anticipated by 2035 c. Green hydrogen costs are expected to decrease significantly by 2035, achieving commercial viability
Hybrid power		a. Significant EMS energy prediction deviations under variable operating conditions b. Protocol interoperability challenges in multi-device communication c. Excessive failure rates in complex sea states	a. Edge AI-based EMS achieves millisecond response via local real-time decision-making b. Joint framework development by major manufacturers c. Real-time monitoring using digital twin and AI diagnostics	a. Edge AI EMS projected to reach $\pm 3\%$ prediction accuracy by 2025 [98] b. Concentrated ammonia/hydrogen vessel deliveries (~2027) accelerating protocol integration c. Digital twin + AI diagnostics coverage expected during 2030–2035
Range-extended power		a. Suboptimal peak efficiency of diesel range extenders b. Immature core component supply chain	a. Implementation of Variable Speed Generators (VSG) b. Technological breakthroughs in core component	a. VSG technology is expected to exceed 95% system efficiency by 2027 b. Domestic production capability for core components expected by 2030

As can be seen from the Table 7, the decarbonization pathway for inland waterway vessel power systems exhibits a distinct phased progression pattern. During the initial transition phase (2025–2030), LNG power systems maintain dominance until 2027, supported by expanding bunkering networks and methane slip mitigation. Methanol power systems are projected to gain traction around 2030 with variable compression ratio penetration and green methanol production scaling. Hybrid power systems proliferate in medium cargo vessels through intelligent management upgrades. Pure electric power technology remains confined to short-range applications.

The subsequent phase (2030–2035) marks the commercialization of zero-carbon fuels and scaling of pure electric technologies. During this stage, it is anticipated that the supply chain for green ammonia will expand, and ammonia fuel power systems will gradually mature, leading to large-scale adoption in container ships and bulk carriers. Concurrently, breakthroughs in solid-state batteries and fuel cells, coupled with declining green hydrogen costs, drive gradual penetration of pure electric systems in small-to-medium inland cargo vessels.

Post-2035, zero-carbon powertrains progressively dominate inland waterway vessel power systems. Based on current research trends, it is projected that by 2035, the green ammonia supply chain will be largely mature, with costs comparable to conventional fuels, making it a primary fuel for inland vessel power systems. Concurrently, solid-state batteries exhibit significant cost advantages, driving installation rates exceeding 50% in small-to-medium inland cargo vessels, while SOFC/PEMFC fuel cell power systems attain target lifespan and efficiency metrics. Supported by well-developed green hydrogen bunkering networks, these fuel cell systems achieve commercial deployment in high-speed passenger vessels and similar applications.

4. Conclusions

This study addressed the decarbonization requirements for energy and propulsion systems of inland waterway vessels in the Yangtze River, summarizing and evaluating the

application value and potential of different energy and power configurations for inland vessels. The emission reduction potential of technologies such as diesel, LNG, methanol, ammonia, pure electric and hybrid power was systematically explored. Combining these with the operational characteristics of vessels across different voyage profiles, suggestions for the selection of power systems suitable for the current low-carbon transformation stage were proposed. Finally, a staged forecast is provided for the application prospects of various energy and power technologies in inland vessels. Key conclusions are summarized as follows:

1. Cleaner conventional powertrains represent the core short-term decarbonization pathway. LNG power systems remain the mainstream choice for medium- and long-distance dry bulk carriers and container ships. There is an urgent need to accelerate the development of the LNG bunkering network along the main trunk of the Yangtze River, aiming for coverage exceeding 60% by 2027, and to promote the application of low-methane slip combustion technologies such as NextDF. Methanol power systems demonstrate favorable techno-economic performance for short- and medium-distance vessels. It is recommended to promote the deployment of green methanol production capacity through policy support and establish a standard system for methanol bunkering. Hybrid power systems, leveraging optimized coordination between engines and batteries, achieve significant energy consumption reductions in medium-sized cargo vessels. It is advised to prioritize the retrofitting of existing vessels with hybrid systems between 2025 and 2030, focusing initially on bulk carriers and container ships in the 500–2000 tons class. Efforts should accelerate the development of edge AI-based intelligent energy management systems and promote the standardization of equipment communication protocols to reduce energy consumption deviations under varying conditions and enhance system reliability.
2. Breakthroughs in Pure electric and zero-carbon fuel technologies are pivotal for medium- to long-term emission reduction. Pure electric vessels are already commercially viable in short-distance passenger transport and port operations. The application of high-rate LFP batteries should be promptly advanced in ferries and patrol boats, supported by the construction of shore-based fast-charging and battery-swapping facilities, alongside demonstration projects for solid-state battery marine applications. For fuel cells, addressing service life and cost issues is critical. It is recommended to promote their use in high-speed passenger vessels through the scaled production of green hydrogen. As an ultimate zero-carbon solution, ammonia fuel efforts between 2025 and 2030 should focus on validating pre-chamber ignition and corrosion-resistant materials, simultaneously establishing demonstration production lines for green ammonia and pilot bunkering projects for inland waterways.
3. The current low-carbon transition for inland vessels in the Yangtze River Basin requires precise power system selection tailored to voyage distance. For short-distance vessels, high-rate LFP battery packs paired with permanent magnet synchronous motor propulsion systems are recommended. Intelligent battery management can reduce idle energy consumption, meeting zero-emission requirements in ports and environmentally sensitive areas. Medium-distance vessels are better suited to methanol-battery hybrid architectures, utilizing operational switching between “electric mode at low speeds and methanol mode at high speeds”. This leverages green methanol’s lifecycle emission reduction advantages and the battery’s power compensation capability to increase the proportion of time the engine operates within its high-efficiency range. Long-distance vessels should prioritize LNG-battery hybrid systems, relying on LNG for primary endurance to meet long-range demands, supplemented by

battery packs for pure electric mode in congested segments to reduce idle losses, potentially lowering CO₂ emissions by 24% over the lifecycle.

4. The future green transition of power systems for inland vessels in the Yangtze River Basin should follow a phased strategy, reliant on the synergistic advancement of technology development, policy support, and infrastructure construction. The period from 2025 to 2030 should be a transition phase dominated by LNG/methanol fuels and hybrid power systems, primarily leveraging existing infrastructure to achieve short-term emission reductions. The focus between 2030 and 2035 should be on scaling up the application of ammonia fuel power systems in inland vessels and commercializing solid-state batteries. Post-2035, the sector should gradually enter a zero-carbon power dominance phase, relying on mature green ammonia/green hydrogen industrial chains to achieve full lifecycle decarbonization for newly built vessels in the Yangtze River Basin. To ensure a smooth transition, it is recommended that policy measures include implementing environmental performance-based differentiated port fee systems, exploring incentive mechanisms such as carbon tax exemptions, and accelerating the establishment of a unified ship carbon accounting and monitoring platform to provide institutional support and data foundation for the transition process.

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Abbreviations

The following abbreviations are used in this manuscript:

LNG	Liquefied Natural Gas
LBG	Liquefied Biogas
IMO	International Maritime Organization
BOG	Boil-off Gas
EGR	Exhaust Gas Recirculation
SCR	Selective Catalytic Reduction
PEMFC	Proton Exchange Membrane Fuel Cell
SOFC	Solid Oxide Fuel Cell
LFP	Lithium Iron Phosphate

NCM	Nickel-Cobalt-Manganese
NCA	Nickel-Cobalt-Aluminum
MCFC	Molten Carbonate Fuel Cell
AFC	Alkaline Fuel Cell
PAFC	Phosphoric Acid Fuel Cell
DMFC	Direct Methanol Fuel Cell
HT-PEMFC	High-Temperature Proton Exchange Membrane Fuel Cell
EMS	Energy Management Strategy
IEC	International Electrotechnical Commission
VSG	Variable Speed Generator
CCT	Carbon Cap-and-Trade scheme
RSB	Roundtable on Sustainable Biomaterials
HPDI	High-Pressure Direct Ignition
ISCC	International Sustainability and Carbon Certification
VCR	Variable Compression Ratio

References

1. Tsinghua University. Global Inland Waterway and Coastal Shipping Management and Emissions. 2023. Available online: <https://www.efchina.org/Reports-zh/report-ctp-202300926-zh> (accessed on 20 June 2025).
2. Ministry of Transport of the People's Republic of China (MOT). The Statistical Communique on the Development of the Transportation Industry in 2022. 2023. Available online: https://www.gov.cn/lianbo/bumen/202306/content_6887539.htm (accessed on 25 June 2025).
3. Peng, X.; Ding, Y.; He, K.; Yi, W.; Luo, Z.; Laroussi, I. Decoupling dynamics: Evaluating the relationship between ship emissions and socioeconomic progress in the Yangtze River Basin from 2007 to 2022. *J. Clean. Prod.* **2024**, *460*, 142632. [\[CrossRef\]](#)
4. Wang, Z.; Tang, H.; Wu, Z.; Ji, Y.; Han, F. Evaluating fuel cell power systems for coastal and inland waterway vessels: Technical and economic perspectives. *Energy Convers. Manag.* **2025**, *323*, 119200. [\[CrossRef\]](#)
5. Camargo-Díaz, C.P.; Paipa-Sanabria, E.; Zapata-Cortes, J.A.; Aguirre-Restrepo, Y.; Quiñones-Bolaños, E.E. A review of economic incentives to promote decarbonization alternatives in maritime and inland waterway transport modes. *Sustainability* **2022**, *14*, 14405. [\[CrossRef\]](#)
6. Tan, Z.; Shao, S.; Zhang, D.; Shang, W.L.; Ochieng, W.; Han, Y. Decarbonizing the inland container fleet with carbon cap-and-trade scheme. *Appl. Energy* **2024**, *376*, 124251. [\[CrossRef\]](#)
7. Issa, M.; Ilinca, A.; Martini, F. Ship energy efficiency and maritime sector initiatives to reduce carbon emissions. *Energies* **2022**, *15*, 7910. [\[CrossRef\]](#)
8. Palomba, G.; Scattareggia Marchese, S.; Crupi, V.; Garbatov, Y. Cost, energy efficiency and carbon footprint analysis of hybrid light-weight bulk carrier. *J. Mar. Sci. Eng.* **2022**, *10*, 957. [\[CrossRef\]](#)
9. Wang, Z.; Wang, K.; Huang, L.; Chen, J.; Chen, W. Dynamic optimization method of ship speed based on sea condition recognition. *J. Harbin Eng. Univ.* **2022**, *43*, 488–494.
10. Sebos, I. Fossil Fraction of CO₂ Emissions of Biofuels. *Carbon Manag.* **2022**, *13*, 154–163. [\[CrossRef\]](#)
11. Thiagarajan, S.; Geo, V.E.; Martin, L.J.; Nagalingam, B. Comparative Analysis of Various Methods to Reduce CO₂ Emission in a Biodiesel Fueled CI Engine. *Fuel* **2019**, *253*, 146–158. [\[CrossRef\]](#)
12. Huuskonen, S.; Karjalainen, J.; Poikela, A.; Venäläinen, P.; Riekk, K.; Helo, P.; Kauranen, P.; Tilli, A.; Kärhä, K. Greenhouse Gas Emissions, Energy and Cost-Efficiencies Associated with Liquefied Biogas-Powered Heavy-Duty Timber Trucks in Industrial Roundwood Transportation. *J. Clean. Prod.* **2025**, *521*, 146215. [\[CrossRef\]](#)
13. Kolodziejewski, M.; Sosnowski, M. Review of Wind-Assisted Propulsion Systems in Maritime Transport. *Energies* **2025**, *18*, 897. [\[CrossRef\]](#)
14. Kasaeian, A.; Zarkhah, N.; Dezfouli, P.A.; Samankan, S.; Yan, W.M. A Review of the Applications of Solar Photovoltaic in Marine Vessels and Ships. *Appl. Energy* **2025**, *396*, 126178. [\[CrossRef\]](#)
15. Yan, X.; He, Y.; Fan, A. Carbon footprint prediction considering the evolution of alternative fuels and cargo: A case study of Yangtze river ships. *Renew. Sustain. Energy Rev.* **2023**, *173*, 113068. [\[CrossRef\]](#)
16. Fan, A.; Wang, J.; He, Y.; Perčić, M.; Vladimir, N.; Yang, L. Decarbonising inland ship power system: Alternative solution and assessment method. *Energy* **2021**, *226*, 120266. [\[CrossRef\]](#)
17. Feng, Y.; Dai, L.; Yue, M.; Hu, H.; Fang, S. Assessing the decarbonization potential of electric ships for inland waterway freight transportation. *Transp. Res. D Transp. Environ.* **2024**, *129*, 104151. [\[CrossRef\]](#)

18. Wang, Y.; Xiao, X.; Ji, Y. A review of LCA studies on marine alternative fuels: Fuels, methodology, case studies, and recommendations. *J. Mar. Sci. Eng.* **2025**, *13*, 196. [CrossRef]
19. Bei, Z.; Wang, J.; Li, Y.; Wang, H.; Li, M.; Qian, F.; Xu, W. Challenges and solutions of ship power system electrification. *Energies* **2024**, *17*, 3311. [CrossRef]
20. Peng, Z.; Wang, L.; Tong, L.; Zhang, C.; Zou, H.; Tan, J. Establishment of inland ship air pollution emission inventory based on power method correction model. *Sustainability* **2022**, *14*, 11188. [CrossRef]
21. Zhang, C.; Ringsberg, J.W.; Thies, F. Development of a ship performance model for power estimation of inland waterway vessels. *Ocean Eng.* **2023**, *287*, 115731. [CrossRef]
22. Yan, X.; Wang, K.; Yuan, Y.; Jiang, X.; Negenborn, R.R. Energy-efficient shipping: An application of big data analysis for optimizing engine speed of inland ships considering multiple environmental factors. *Ocean Eng.* **2018**, *169*, 457–468. [CrossRef]
23. China Waterborne Transport Research Institute, Ministry of Transport. Waterborne Transport Science & Technology. 2024. Available online: <https://www.wti.ac.cn/wti/u/cms/www/202407/091338091mx6.pdf> (accessed on 20 August 2025).
24. Alizadeh, A.H.; Talley, W.K. Vessel and Voyage Determinants of Tanker Freight Rates and Contract Times. *Transp. Policy* **2011**, *18*, 665–675. [CrossRef]
25. Peng, X.; Ding, Y.; Yi, W.; Laroussi, I.; He, T.; He, K.; Liu, H. The inland waterway ship emission inventory modeling: The Yangtze River case. *Transp. Res. Part D Transp. Environ.* **2024**, *129*, 104138. [CrossRef]
26. Nishimuro, M. Roadmap to zero emission from international shipping. *ClassNK Tech. J.* **2020**, *1*, 13–20.
27. Al-Douri, A.; Alsuhaibani, A.S.; Moore, M.; Nielsen, R.B.; El-Baz, A.A.; El-Halwagi, M.M. Greenhouse gases emissions in liquified natural gas as a marine fuel: Life cycle analysis and reduction potential. *Can. J. Chem. Eng.* **2022**, *100*, 1178–1186. [CrossRef]
28. Kayä, G.; Bolat, F.Ä. Evaluation of the Turkish marine trade fleet in terms of ship sizes and main engine powers. *Eurasian Econom. Stat. Empir. Econ. J.* **2021**, *18*, 44–63.
29. Li, Z.; Zhang, Z.; Fan, Y.; Li, J.; Wu, K.; Gao, Z.; Li, A.; Zhu, L.; Huang, Z. Fuel reactivity stratification assisted jet ignition for low-speed two-stroke ammonia marine engine. *Int. J. Hydrogen Energy* **2024**, *49*, 570–585. [CrossRef]
30. Yang, R.; Yang, X.; Shao, X.; Zheng, H.; Zhao, N. Thermodynamic performance simulation of NH₃ based chemically recuperated cycle gas turbine. *J. Aerosp. Power* **2024**, *39*, 20220993.
31. Wang, H.; Sun, K.; Feng, Y.; Wang, T. Analysis of the greenhouse gas emissions characteristics of an ammonia-diesel dual fuel low-speed marine engine. *Trans. CSICE* **2024**, *42*, 385–393.
32. Li, D.; Yang, H.; Xing, Y. Economic and emission assessment of LNG-fuelled ships for inland waterway transportation. *Ocean Coast. Manag.* **2023**, *246*, 106906. [CrossRef]
33. Wang, D.; Liu, X.; Ni, Z.; Liu, Y. Challenges and innovation that will be brought to maritime education by the rapid development of shipping technology. *Am. J. Traffic Transp. Eng.* **2023**, *8*, 113–118. [CrossRef]
34. Kuittinen, N.; Koponen, P.; Vesala, H.; Lehtoranta, K. Methane slip and other emissions from newbuild LNG engine under real-world operation of a state-of-the art cruise ship. *Atmos. Environ. X* **2024**, *23*, 100285. [CrossRef]
35. Parris, D.; Spinthiropoulos, K.; Ragazou, K.; Giovou, A.; Tsanaktsidis, C. Methanol, a plugin marine fuel for green house gas reduction—A review. *Energies* **2024**, *17*, 605. [CrossRef]
36. Chen, D.; Wang, T.; Yang, T.; Li, G.; Chen, Y.; Qiao, T. Effects of EGR Combined with DOC on Emission Characteristics of a Two-Stage Injected Fischer-Tropsch Diesel/Methanol Dual-Fuel Engine. *Fuel* **2022**, *329*, 125451. [CrossRef]
37. Wang, P.; Long, W.; Zhao, W.; Dong, P.; Lu, M.; Wang, Y.; Tian, H.; Xiao, G.; Cui, J.; Liu, X. Combustion characteristics of methanol engine applying -HPDI with optimized pre-chamber nozzle structure under different injection and spark strategy. *Energy* **2024**, *312*, 133503. [CrossRef]
38. Yin, X.; Xu, L.; Duan, H.; Wang, Y.; Wang, X.; Zeng, K.; Wang, Y. In-depth comparison of methanol port and direct injection strategies in a methanol/diesel dual fuel engine. *Fuel Process. Technol.* **2023**, *241*, 107607. [CrossRef]
39. Pu, Y.H.; Dejaegere, Q.; Svensson, M.; Verhelst, S. Renewable methanol as a fuel for heavy-duty engines: A review of technologies enabling single-fuel solutions. *Energies* **2024**, *17*, 1719. [CrossRef]
40. Kumar, V.; Agarwal, A.K. Material compatibility aspects and development of methanol-fueled engines. In *Advanced Combustion Techniques and Engine Technologies for the Automotive Sector*; Springer: Singapore, 2019; pp. 37–51.
41. Li, P.; Lin, J.; Yu, Z.; Chi, Y.; Zhao, K. Feasibility study of renewable e-methanol production: A substitution pathway from blue to green. *iEnergy* **2024**, *3*, 108–114. [CrossRef]
42. Tornatore, C.; Marchitto, L.; Sabia, P.; De Joannon, M. Ammonia as green fuel in internal combustion engines: State-of-the-art and future perspectives. *Front. Mech. Eng.* **2022**, *8*, 944201. [CrossRef]
43. Chen, H.; Li, Y.; Jiang, X.; Du, J.; Li, Y.; Zhan, W. Experimental study on gasoline-ammonia combustion characteristics with pre-chamber jet ignition. *J. Energy Inst.* **2023**, *111*, 101429. [CrossRef]
44. Zhou, X.; Li, T.; Yang, W. Ammonia-Hydrogen Engine with Single Ammonia Fuel Supply. *Joule* **2025**, *9*, 101922. [CrossRef]
45. Zhang, Z.; Di, L.; Shi, L.; Yang, X.; Cheng, T.; Shi, C. Effect of liquid ammonia HPDI strategies on combustion characteristics and emission formation of ammonia-diesel dual-fuel heavy-duty engines. *Fuel* **2024**, *367*, 131450. [CrossRef]

46. Hong, C.; Ji, C.; Wang, S.; Xin, G.; Wang, Z.; Meng, H.; Yang, J. An experimental study of various load control strategies for an ammonia/hydrogen dual-fuel engine with the Miller cycle. *Fuel Process. Technol.* **2023**, *247*, 107780. [[CrossRef](#)]
47. Lesmana, H.; Zhang, Z.; Li, X.; Zhu, M.; Xu, W.; Zhang, D. NH₃ as a transport fuel in internal combustion engines: A technical review. *J. Energy Resour. Technol.* **2019**, *141*, 070703. [[CrossRef](#)]
48. Koike, M.; Suzuoki, T.; Takeuchi, T.; Homma, T.; Hariu, S.; Takeuchi, Y. Cold-start performance of an ammonia-fueled spark ignition engine with an on-board fuel reformer. *Int. J. Hydrogen Energy* **2021**, *46*, 25689–25698. [[CrossRef](#)]
49. Lee, D.; Song, H.H. Development of combustion strategy for the internal combustion engine fueled by ammonia and its operating characteristics. *J. Mech. Sci. Technol.* **2018**, *32*, 1905–1925. [[CrossRef](#)]
50. Ryu, K.; Zacharakis-Jutz, G.E.; Kong, S.C. Performance enhancement of ammonia-fueled engine by using dissociation catalyst for hydrogen generation. *Int. J. Hydrogen Energy* **2014**, *39*, 2390–2398. [[CrossRef](#)]
51. Huang, Q.; Liu, J. Preliminary assessment of the potential for rapid combustion of pure ammonia in engine cylinders using the multiple spark ignition strategy. *Int. J. Hydrogen Energy* **2024**, *55*, 375–385. [[CrossRef](#)]
52. Li, Z.; Li, S. Effects of inter-stage mixing on the NO_x emission of staged ammonia combustion. *Int. J. Hydrogen Energy* **2022**, *47*, 9791–9799. [[CrossRef](#)]
53. Yamashita, H.; Hayakawa, A.; Okafor, E.C.; Colson, S.; Somarathne, K.K.A.; Tsujimura, T.; Ito, S.; Uchida, M.; Kudo, T.; Kobayashi, H. Optimum primary equivalence ratio for rich-lean two-stage combustion of non-premixed ammonia/methane/air and ammonia/hydrogen/air flames in a swirling flow. *Fuel* **2024**, *368*, 131598. [[CrossRef](#)]
54. Shin, J.; Park, S. Numerical analysis for optimizing combustion strategy in an ammonia-diesel dual-fuel engine. *Energy Convers. Manag.* **2023**, *284*, 116980. [[CrossRef](#)]
55. Erdemir, D.; Dincer, I. A perspective on the use of ammonia as a clean fuel: Challenges and solutions. *Int. J. Energy Res.* **2021**, *45*, 4827–4834. [[CrossRef](#)]
56. Cai, Y.; Wang, Z.; Tang, Y.; Xu, C.; Song, Y.; Dong, K.; Han, E.H. Corrosion fatigue behavior of cast iron in simulated combustion product solutions of ammonia and methanol fuels. *Int. J. Fatigue* **2025**, *191*, 108715. [[CrossRef](#)]
57. Djermouni, M.; Ouadha, A. Thermodynamic analysis of methanol, ammonia, and hydrogen as alternative fuels in HCCI engines. *Int. J. Thermofluids* **2023**, *19*, 100372. [[CrossRef](#)]
58. Zhou, X.; Li, T.; Wang, N.; Wang, X.; Chen, R.; Li, S. Pilot diesel-ignited ammonia dual fuel low-speed marine engines: A comparative analysis of ammonia premixed and high-pressure spray combustion modes with CFD simulation. *Renew. Sustain. Energy Rev.* **2023**, *173*, 113108. [[CrossRef](#)]
59. Song, Q.; Tinoco, R.R.; Yang, H.; Yang, Q.; Jiang, H.; Chen, Y.; Chen, H. A comparative study on energy efficiency of the maritime supply chains for liquefied hydrogen, ammonia, methanol and natural gas. *Carbon Capture Sci. Technol.* **2022**, *4*, 100056. [[CrossRef](#)]
60. Shamsul, N.S.; Kamarudin, S.K.; Rahman, N.A.; Kofli, N.T. An overview on the production of bio-methanol as potential renewable energy. *Renew. Sustain. Energy Rev.* **2014**, *33*, 578–588. [[CrossRef](#)]
61. Seo, Y.; An, J.; Park, E.; Kim, J.; Cho, M.; Han, S.; Lee, J. Technical–economic analysis for ammonia ocean transportation using an ammonia-fueled carrier. *Sustainability* **2024**, *16*, 827. [[CrossRef](#)]
62. Brynolf, S.; Fridell, E.; Andersson, K. Environmental assessment of marine fuels: Liquefied natural gas, liquefied biogas, methanol and bio-methanol. *J. Clean. Prod.* **2014**, *74*, 86–95. [[CrossRef](#)]
63. Iribarren, D.; Calvo-Serrano, R.; Martín-Gamboa, M.; Galan-Martin, A.; Guillen-Gosalbez, G. Social Life Cycle Assessment of Green Methanol and Benchmarking against Conventional Fossil Methanol. *Sci. Total Environ.* **2022**, *824*, 153840. [[CrossRef](#)]
64. Mohan, S.; Dinesha, P.; Kumar, S. NO_x reduction behaviour in copper zeolite catalysts for ammonia SCR systems: A review. *Chem. Eng. J.* **2020**, *384*, 123253. [[CrossRef](#)]
65. Rasul, M.J.M.A.; Kim, J. Comprehensive review and comparison on battery technologies as electric-powered source in marine applications. *J. Energy Storage* **2024**, *88*, 111509. [[CrossRef](#)]
66. Zhang, Y.; Sun, L.; Ma, F.; Wu, Y.; Jiang, W.; Fu, L. Collaborative optimization of the battery capacity and sailing speed considering multiple operation factors for a battery-powered ship. *World Electr. Veh. J.* **2022**, *13*, 40. [[CrossRef](#)]
67. Shammugam, S. *Raw Materials and Energy Transformation Process: Analysis of Supply Bottlenecks and Implications on Metal Markets*; Shaker Verlag: Aachen, Germany, 2019.
68. Helgesen, H.; Henningsgard, S.; Langli, A.A. *Study on Electrical Energy Storage for Ships*; Technical Report; DNVGL: Høvik, Norway, 2020.
69. Joshi, A.; Mishra, D.K.; Singh, R.; Zhang, J.; Ding, Y. A Comprehensive Review of Solid-State Batteries. *Appl. Energy* **2025**, *386*, 125546. [[CrossRef](#)]
70. Xing, H.; Stuart, C.; Spence, S.; Chen, H. Fuel cell power systems for maritime applications: Progress and perspectives. *Sustainability* **2021**, *13*, 1213. [[CrossRef](#)]

71. Wang, X.; Zhu, J.; Han, M. Industrial development status and prospects of the marine fuel cell: A review. *J. Mar. Sci. Eng.* **2023**, *11*, 238. [\[CrossRef\]](#)
72. Corigliano, O.; Pagnotta, L.; Fragiaco, P. On the Technology of Solid Oxide Fuel Cell (SOFC) Energy Systems for Stationary Power Generation: A Review. *Sustainability* **2022**, *14*, 15276. [\[CrossRef\]](#)
73. Qasem, N.A.A.; Abdulrahman, G.A.Q. A Recent Comprehensive Review of Fuel Cells: History, Types, and Applications. *Int. J. Energy Res.* **2024**, *2024*, 7271748. [\[CrossRef\]](#)
74. Peng, S. *Hydrogen Fuel Cells*; Springer: Singapore, 2024; pp. 143–165.
75. Shaari, N.; Kamarudin, S.K.; Bahru, R.; Osman, S.H.; Md Ishak, N.A.I. Progress and Challenges: Review for Direct Liquid Fuel Cell. *Int. J. Energy Res.* **2021**, *45*, 6644–6688. [\[CrossRef\]](#)
76. Radica, G.; Tolj, I.; Nyamsi, S.N.; Vidović, T. Performances of proton exchange membrane fuel cells in marine application. *Int. J. Hydrogen Energy* **2025**, *142*, 186–194. [\[CrossRef\]](#)
77. DNV. DNV, HD KSOE and HD Hydrogen to Collaborate on CO₂ Capture Technology for SOFCs. 2025. Available online: <https://www.dnv.com/news/2025/dnv-hd-ksoe-and-hd-hydrogen-to-collaborate-on-co2-capture-technology-for-sofcs/> (accessed on 25 June 2025).
78. Wang, J.; Zhou, J.; Zhao, W. Deep reinforcement learning based energy management strategy for fuel cell/battery/supercapacitor powered electric vehicle. *Green Energy Intell. Transp.* **2022**, *1*, 100028. [\[CrossRef\]](#)
79. Łebkowski, A. Reduction of fuel consumption and pollution emissions in inland water transport by application of hybrid powertrain. *Energies* **2018**, *11*, 1981. [\[CrossRef\]](#)
80. Roslan, S.B.; Konovessis, D.; Tay, Z.Y. Sustainable hybrid marine power systems for power management optimisation: A review. *Energies* **2022**, *15*, 9622. [\[CrossRef\]](#)
81. Bui, T.M.N.; Dinh, T.Q.; Marco, J.; Watts, C. Development and real-time performance evaluation of energy management strategy for a dynamic positioning hybrid electric marine vessel. *Electronics* **2021**, *10*, 1280. [\[CrossRef\]](#)
82. Geertsma, R.D.; Negenborn, R.R.; Visser, K.; Hopman, J. Design and control of hybrid power and propulsion systems for smart ships: A review of developments. *Appl. Energy* **2017**, *194*, 30–54. [\[CrossRef\]](#)
83. Truong, H.V.A.; Do, T.C.; Dang, T.D. Enhancing efficiency in hybrid marine vessels through a multi-layer optimization energy management system. *J. Mar. Sci. Eng.* **2024**, *12*, 1295. [\[CrossRef\]](#)
84. Zhu, Y.; Wang, H.; Liu, Y.; Lei, G.; Zhu, J. Multiport energy management system design for a 150 kW range-extended towing vessel. *Appl. Sci.* **2023**, *13*, 12933. [\[CrossRef\]](#)
85. Yuan, Y.; Wang, J.; Yan, X.; Li, Q.; Long, T. A Review of Multi-Energy Hybrid Power System for Ships. *Renew. Sustain. Energy Rev.* **2020**, *132*, 110029. [\[CrossRef\]](#)
86. Liu, H.; Fan, A.; Li, Y.; Bucknall, R.; Vladimir, N. Multi-Objective Hierarchical Energy Management Strategy for Fuel Cell/Battery Hybrid Power Ships. *Appl. Energy* **2025**, *379*, 124981. [\[CrossRef\]](#)
87. Wang, Z.; Liao, P.; Long, F.; Wang, Z.; Han, F. Coordinated Optimization of Multi-Energy Systems in Sustainable Ships: Synergizing Power-to-Gas, Carbon Capture, Hydrogen Blending, and Carbon Trading Mechanisms. *Int. J. Hydrogen Energy* **2025**, *165*, 150755. [\[CrossRef\]](#)
88. Zhou, T.; Hu, Q.; Hu, Z.; Zhen, R. An Adaptive Hyper Parameter Tuning Model for Ship Fuel Consumption Prediction under Complex Maritime Environments. *J. Ocean Eng. Sci.* **2022**, *7*, 255–263. [\[CrossRef\]](#)
89. The Maritime Executive. World's First Dual-Fuel LNG Battery Hybrid PCTC Delivered to UECC. Available online: <https://maritime-executive.com/article/world-s-first-dual-fuel-lng-battery-hybrid-pctc-delivered-to-uecc> (accessed on 28 August 2025).
90. Ammar, N.R.; Seddiek, I.S. Evaluation of the environmental and economic impacts of electric propulsion systems onboard ships: Case study passenger vessel. *Environ. Sci. Pollut. Res.* **2021**, *28*, 37851–37866. [\[CrossRef\]](#)
91. Zhou, Z.; Wu, Z.; Liu, C.; Shao, L.; Zhang, Y.; Liu, W.; Shen, H.; Yao, D.; Fan, H.; Zheng, C.; et al. The path to carbon neutral shipping: A comparative analysis of low carbon technologies. *J. Environ. Sci.* **2025**, *159*, 606–616. [\[CrossRef\]](#)
92. Zhao, F.; Wang, Z.; Wang, D.; Han, F.; Ji, Y.; Cai, W. Top level design and evaluation of advanced low/zero carbon fuel ships power technology. *Energy Rep.* **2022**, *8*, 336–344. [\[CrossRef\]](#)
93. Ministry of Transport of the People's Republic of China (MOT). Layout Plan for LNG Refueling Terminals Along the Yangtze River Trunk Line, Beijing-Hangzhou Grand Canal, and Xijiang Waterway (2017–2025). 2017. Available online: https://xxgk.mot.gov.cn/2020/jigou/zhghs/202006/t20200630_3319981.html (accessed on 28 June 2025).
94. ABS. Regulatory Trends and Impact, 2nd ed. Available online: <https://ww2.eagle.org/en/publication-flip/regulatory-trends-impact.html> (accessed on 28 June 2025).
95. Methanol Institute. Renewable Methanol. Available online: <https://www.methanol.org/renewable> (accessed on 28 June 2025).
96. Shao, T.; Zhang, S.; Zhang, C.; Gao, Y.; Sun, H.; Dou, L.; Xi, D. The strategy and route of renewable energy driven discharge plasma boosting the carbon peak and carbon neutrality. *Proc. CSEE* **2024**, *44*, 7453–7479.

97. Xu, X.; Ge, C.; Zhang, B.; Ma, X.; Guo, R.; Wang, X.; Lu, X. Study on the tribological behaviors of the cylinder liner-piston ring in the ammonia-fueled engine. *Friction* **2025**, *13*, 9440974. [[CrossRef](#)]
98. Jung, W.; Chang, D. Deep reinforcement learning-based energy management for liquid hydrogen-fueled hybrid electric ship propulsion system. *J. Mar. Sci. Eng.* **2023**, *11*, 2007. [[CrossRef](#)]

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