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Review on the Application of New Energy Power in Container Ships: Technical Status and Future Prospects of Hydrogen Power Systems

Zhenhao Yan

Department of Engineering, The Hong Kong Polytechnic University, Hong Kong, China
yzh1356819269@gmail.com

Abstract. Currently, solar and wind energy can only be served as auxiliary propulsion in container ships, which are difficult to replace the main propulsion. Thus, hydrogen power systems have become one of the key directions for zero-carbon shipping, depending on their zero-carbon potential and efficiency advantages. This paper focuses on the application of hydrogen power systems in container ships, specifically examining their technical principles and hydrogen storage methods. It analyzes challenges including constraints on hydrogen storage volume and weight, insufficient salt spray resistance and durability of PEMFC, complex system integration, lagging regulations, and high costs. Additionally, it summarizes the rules of technical application by integrating industry demonstration practices. Due to green hydrogen production, the full-chain low-carbon benefits of these systems and their compatibility with IMO regulations are significant. However, key issues such as the optimization of hydrogen storage technology and the improvement of fuel cell environmental adaptability remain to be addressed. Based on industrial planning forecasts, it is highly likely that the commercialization of hydrogen energy in inland and coastal short-to-medium-distance container ships will be realized within the next decade, while ocean-going ships will require major breakthroughs in areas such as hydrogen storage energy density. This paper can provide references for clarifying the R&D direction of hydrogen-powered ship technologies, constructing policy support systems, and promoting industrial chain collaboration. They will help the shipping industry align with IMO emission reduction targets and advance zero-carbon shipping from the demonstration stage to large-scale commercial application.

Keywords: Container ships, Hydrogen power systems, Proton Exchange Membrane Fuel Cells (PEMFC), Zero-carbon shipping, Hydrogen storage technology

1. Introduction

The shipping industry plays an irreplaceable role in modern international trade, but its environmental costs have attracted increasing global attention. As the main carriers of international and inland freight, ships emit carbon dioxide (CO_2), sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) through fuel combustion, posing significant hazards to both climate change

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and air quality. The International Maritime Organization (IMO) has established a target to reduce the net greenhouse gas emissions of the shipping industry by at least half by 2050 compared with 2008. Meanwhile, it has further tightened regulatory constraints on sulfur emissions, nitrogen oxide emissions, the Energy Efficiency Design Index (EEDI), and the Carbon Intensity Indicator (CII). These requirements have compelled shipping companies, shipyards, and research institutions to consider a fundamental transformation of power systems—not merely fuel replacement, but also a comprehensive analysis of power systems, fuel production, supply infrastructure, and life-cycle emissions.

Against this backdrop, container ships have become one of the focuses of the transition to new energy power. Container ships are characterized by high sailing speeds, long routes, large load fluctuations, and high requirements for reliability and safety. The performance and economy of their power systems are directly related to operating costs and market competitiveness. Research on the application of new energy in container ships mainly focuses on auxiliary solar and wind energy, hybrid power or battery-electric drive, and hydrogen power systems. Solar and wind energy have been applied to a certain extent in auxiliary propulsion and reducing main engine load, but their ability to replace main propulsion remains very limited. In particular, hydrogen power systems centered on fuel cells are regarded as a key means to achieve zero carbon emissions for container ships in both ocean-going and coastal navigation, as they can theoretically achieve zero carbon emissions, offer good efficiency, and have the potential to be combined with renewable energy-based hydrogen production. This review aims to systematically review the development status of solar, wind, and hydrogen energy in container ships, elaborate on the technical principles and advantages of hydrogen power systems, discuss the challenges they face and breakthroughs in key technologies, present typical cases, and prospect the trends of technology and market, so as to provide references for future policy-making and technology R&D.

2. Current application status of new energy in container ships

The application of new energy in container ships is not a single-path process but a joint promotion by multiple methods. Among them, solar and wind energy are mostly used as auxiliary or supplementary power, while hydrogen energy is moving from the experimental and demonstration stages to more practical applications.

The auxiliary application of solar energy is usually realized by laying photovoltaic panels in available areas such as the top of the bridge and container tops to meet the low-power load requirements of lighting, electrical auxiliary systems, refrigerated cabins, ventilation, and navigation auxiliary equipment. This system works better on coastal or equatorial routes with abundant sunlight, but its power generation efficiency decreases significantly under cloudy conditions, at high latitudes, at nighttime, and in rainy weather. In addition, the height and layout of containers often obstruct sunlight, which would limit installation of the photovoltaic panels due to the limited suitable deck area. Issues such as the weight of photovoltaic panels, their salt spray resistance, and maintenance and cleaning also reduce their economic value. Therefore, solar energy generally only plays an auxiliary role in container ships and cannot independently undertake propulsion tasks.

Wind energy is applied in various forms, including passive sails, wing sails, and rotor sails. Among them, active propulsion-aid devices such as wing sails could significantly reduce the main engine load in medium- and short-distance routes with suitable wind conditions or relatively fixed routes, thereby reducing fuel consumption and pollutant emissions. However, container ships have high requirements for sailing speed, and frequent route changes, and the design and installation of large-scale wing sails face significant challenges, center-of-gravity stability and structural strength.

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Under unfavorable wind directions and low wind speeds, the contribution of wind power to propulsion may be minimal, and its promotion is greatly restricted by geographical and meteorological conditions.

China has achieved rapid development in the field of ship hydrogen power systems. If hydrogen is derived from "green hydrogen" produced by renewable energy, hydrogen fuel cells only emit water vapor during operation, without generating CO_2, SO_x, or NO_x—making them one of the key pathways to achieve zero-carbon shipping. Inland and coastal demonstration projects have begun to enter the implementation stage, with the "Dongfang Qinggang" ship project being the most representative. According to officially released information, the ship has an overall length of approximately 64.5 meters, a molded breadth of 12.6 meters, a molded depth of 3.55 meters, and a draft of 2.75 meters. It can carry 64 standard containers with a cargo capacity of approximately 1,450 tons. The ship adopts two sets of 240 kW hydrogen fuel cell stacks manufactured by domestic enterprises as the sole energy supply source and is equipped with a hydrogen storage system capable of storing approximately 550 kg of hydrogen. According to official reports, the ship has a cruising range of approximately 380 kilometers and operates on the inland shipping route between Zhapu Port and Xiasha Port. The system still includes lithium batteries, a propulsion control system, a hydrogen supply system, and a digital control system, all of which are integrated with the fuel cell and hydrogen storage systems to address load fluctuations and safety control requirements. The project was launched at the end of 2024 and "plans to carry out operational demonstrations on the inland shipping route between Zhapu Port and Xiasha Port". This project marks a milestone in the large-scale application of hydrogen fuel cells in China's container transportation field and leads similar domestic projects in terms of hydrogen storage scale and integration level [1,2].

Although the mature commercial application of hydrogen-based main propulsion has not been widely implemented in practical applications of large ocean-going container ships, it has become a key area for testing and demonstrating fuel cell and hydrogen storage technologies in ferries, coastal feeder freight ships, and inland ships. These cases not only verify the feasibility of the technology but also accumulate experience in marine durability, safety standards, and supply infrastructure.

3. Technical principles and advantages of hydrogen power systems

The core of a hydrogen power system is the fuel cell, which utilizes an electrochemical reaction between hydrogen and oxygen. Hydrogen molecules dissociate into protons and electrons, protons migrate to the cathode through the electrolyte membrane, while electrons generate an electric current through an external circuit. Oxygen combines with electrons and protons to form water. Unlike combustion processes, this process theoretically does not produce combustion products such as CO_2, SO_x or NO_x.

There are various types of fuel cells. Proton Exchange Membrane Fuel Cells (PEMFC) feature fast start-up and high-power density, making them suitable for auxiliary propulsion, hybrid power, or short-distance scenarios in ships. Solid Oxide Fuel Cells (SOFC) offer higher efficiency at high temperatures but have strict requirements for the heat resistance and cycle stability of materials, and are often used as auxiliary power sources or for long-term stable load applications.

Hydrogen storage is a key aspect in the design of hydrogen power systems. High-pressure gaseous hydrogen storage technology has achieved maturity, with the advantages of relatively low production and storage costs and clear technical risks. However, it has low volumetric energy density, requires heavy pressure vessels, occupies a certain amount of space, and involves high complexity in center-of-gravity arrangement and safety design. Liquid hydrogen storage can significantly improve volumetric energy density but requires cryogenic insulation and management

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of boil-off loss. Insulation systems, insulation materials, cryogenic pumps, and pipelines all need to adapt to the marine and ship dynamic environment. Compared with solid or semi-solid hydrogen storage methods such as metal hydrides, Liquid Organic Hydrogen Carriers (LOHC) have advantages in safety and ambient-temperature storage stability. However, issues such as energy consumption during dehydrogenation, catalyst performance, and system weight and volume have not been fully resolved under large-scale navigation or frequent start-stop conditions.

These technical combinations enable hydrogen power systems to exhibit multiple advantages in container ships. In terms of environmental benefits, if hydrogen is produced using renewable energy sources (such as wind, solar energy, or water electrolysis), carbon emissions throughout the fuel chain from production to use will be significantly reduced. Under partial and medium load conditions, fuel cells are more efficient than traditional internal combustion engines, and their mechanical vibration and operating noise are also significantly lower—this can improve the smoothness of ship operation and crew comfort, thereby reducing maintenance requirements. In an environment of increasingly strict regulatory and policy pressures, zero-carbon or low-carbon power systems will become part of shipowners' competitive advantages. Hybrid systems (fuel cells + battery energy storage + auxiliary energy) allow flexible responses to route load fluctuations, start-stop conditions, and short-term demand peaks, providing support for the overall efficiency and economy of the system.

4. Challenges and key technologies of hydrogen power systems

To achieve widespread commercial application of hydrogen power systems in container ships, there are several major challenges that remain to be addressed.

First, the volume and weight issues of hydrogen storage are still obvious. Although the design of high-pressure gaseous hydrogen storage is already mature, the excessive weight and high-volume ratio of pressure vessels impose constraints on hull design, container layout and center-of-gravity stability. Compared with gaseous hydrogen, liquid hydrogen has better volumetric density but requires cryogenic insulation, and complex insulation and cooling systems. Improper management of liquid hydrogen boil-off loss would lead to significant energy and economic losses. Besides, issues such as the low-temperature tolerance of materials for liquid hydrogen, energy consumption during liquefaction, and safety assurance must be addressed before extensive commercial use.

Second, the durability and reliability of fuel cells in marine or inland salt spray environments are core challenges, especially for Proton Exchange Membrane Fuel Cells (PEMFC). A recent systematic study on the impact of the "marine salt spray environment" on PEMFC performance found that as the concentration of ions such as Na^+, Ca^{2+}, Mg^{2+}, and K^+ in the air gradually increases, the voltage of the fuel cell decreases significantly under high current density conditions, with Ca^{2+} having a greater impact than other ions. Under unpolluted conditions, the voltage is approximately 0.645 V at a current density of 1 A/cm², after pollution, the voltage drops to approximately 0.594 V, 0.583 V, and 0.559 V respectively, and in some extreme cases, the voltage even drops to approximately 0.300 V. Ion pollution weakens PEMFC performance, and this effect is closely related to the concentration and type of pollutants [3,4].

In addition, components of the fuel cell system, such as materials, electrode catalysts, membranes, electrode diffusion layers, and bipolar plates, must undergo rigorous verification and improvement in actual ship operating environments. For instance, long-term maintenance under dynamic loads, frequent start-stop operating environments, the effects of waves and vibrations, and the corrosion resistance and sealing performance of electrical and structural components. These include issues such as the corrosion of bipolar plates in air environments containing anions such as

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Cl^- and F^- as well as metal ions, the reduction in active sites of oxygen reduction reaction catalysts (e.g., Pt/C) due to ion adsorption or damage, and the deterioration of proton conductivity in the electrolyte membrane [4].

Relevant reviews point out that there is currently insufficient systematic understanding of the degradation mechanisms and research gaps of PEMFC in marine environments. Sufficient experimental verification has not been conducted on aspects such as the long-term effects of low-concentration NaCl in salt spray, mechanical strain caused by ship motion and the effect of residues from hydrogen carrier agents [5].

Third, the complexity of system integration and energy management is considerable. From fuel supply to the fuel cells, such as including hydrogen production, storage, transportation, refueling facilities, battery energy storage, auxiliary energy, load regulation, and control systems within the power system, each component requires coordinated adaptation. Container ships often experience large load changes, such as departure, acceleration, switching between heavy and light loads, berthing and rapid load reduction when docked. Under these conditions, fuel cell efficiency may decrease and their lifespan may be impaired. To address this problem, a hybrid system design is usually adopted: fuel cells undertake continuous medium-to-high loads, battery energy storage or supercapacitors handle peak and transient loads, and auxiliary energy sources such as solar and wind energy are introduced as supplementary or backup energy inputs to reduce load fluctuations on batteries and fuel cells.

Fourth, the development of safety and regulatory standards lags behind. Hydrogen, as a fuel medium, exhibits flammable and explosive properties. And there are potential hazards in hydrogen storage due to pressure or low-temperature conditions, leakage and refueling operations. The International Maritime Organization (IMO), national maritime safety authorities, and classification societies have formulated preliminary guidelines or interim standards for fuel cell ships, hydrogen storage devices, hydrogen refueling facilities, safety standards and inspection rules. However, most of these standards are still in the development or demonstration stage, and more comprehensive, mandatory, and operable rules are needed.

Fifth, cost issues remain prominent. The cost of producing green hydrogen through methods such as electrolysis using large amounts of renewable energy is still high. And the economy of fuel cell systems and hydrogen storage devices, which includes manufacturing, installation, maintenance and lifespan, has not been fully verified by the market.

Finally, referring to the key technological breakthroughs, several directions are currently in the research and testing stage. For example, in the field of electrode catalysts, it is necessary to reduce the usage of precious metals such as platinum and adopt platinum-group metal-free (PGM-free) catalysts, improve the corrosion resistance and salt spray resistance of bipolar plate and diffusion layer materials, modify membrane materials to enhance proton conductivity and pollution resistance, use composite materials for hydrogen storage container materials to reduce weight and improve strength, optimize insulation and boil-off management for liquid hydrogen storage, and advance real-time control systems, digital monitoring, and predictive maintenance in system integration.

5. Typical case analysis: comparison between "Dongfang Qinggang" and international cases

As one of the key cases in China's current demonstration of hydrogen-powered containers, the "Dongfang Qinggang (Eastern Hydrogen Port)" project has provided valuable experience in terms of technical composition and operation model.

By comparison, the Dutch H2 Barge 1 project, initiated by Future Proof Shipping, is a relatively mature demonstration case. The ship is a 110-meter-long, 11.45-meter-wide zero-emission inland

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container ship, leased to BCTN, which operates it on behalf of Nike EMEA. The ship makes multiple round trips weekly between Rotterdam and the inland terminal in Meerhout (Belgium) and is expected to reduce greenhouse gas emissions by approximately 2,000 tons of CO_2 equivalent annually. Its propulsion system achieves zero emissions through a configuration of fuel cells and electric drive [6]. Although public data indicate that the H2 Barge 1 may be inferior to the "Dongfang Qinggang" in some design parameters such as scale (e.g., length, capacity) and cruising range, the experience it has accumulated in hybrid system design, safety certification processes, operational practices, and commercial and leasing models holds strong reference value for the development of hydrogen-powered container ships in China and globally.

6. Development trends and prospects of hydrogen-powered container ships

Based on current technological advancements and demonstration cases, several trends could be identified and potential development paths over the next 10–20 years could be projected.

Technically, the power scale and power density of fuel cells are expected to increase generally. With the development of the materials science and the progression of the manufacturing processes, the durability of PEMFC and similar fuel cell types will be improved. PGM-free catalysts and hybrid electrode designs may significantly reduce costs while enhancing stability in seawater and dynamic operating conditions. The corrosion resistance of bipolar plate and diffusion layer materials would also be enhanced and membrane materials would exhibit stronger pollution and chemical erosion resistance.

In addition, hydrogen storage methods will become more diversified and optimized. Currently, the "Dongfang Qinggang" adopts high-pressure gaseous hydrogen storage as the main method, which is a feasible solution for inland short-distance and medium-distance navigation. However, in coastal or ocean-going navigation routes, the advantage of liquid hydrogen storage in volumetric density will become increasingly critical. Although LOHC and metal hydride carriers currently face challenges in dehydrogenation efficiency and system weight, their potential in safety and ambient-temperature storage stability may make them become key components of ocean-going or alternative hydrogen storage methods in the future.

Third, system integration and hybrid energy architectures will become standard configurations. Fuel cells, battery energy storage facilities, auxiliary solar or wind energy, and optimized control methods will work together to improve efficiency, reduce fuel consumption, and extend equipment lifespan. Energy management systems will further rely on digital monitoring and predictive maintenance to real-time monitor risk factors, which could ensure the safety and reliability during operation. For instance, fuel cell status, hydrogen storage status, temperature, pressure and leakage.

Fourth, in the regulatory and policy environment, the reduction in green hydrogen production costs and the strengthening of carbon pricing mechanisms and carbon tax systems will boost the economy of hydrogen power systems. Governments need to further promote the construction of green shipping corridors, including the deployment of hydrogen refueling facilities between ports. Policy subsidies, tax incentives, and investment support will also help share the initial cost investments of hydrogen power systems.

Fifth, market competitiveness and operation models will undergo changes. Shipowners and shippers are increasingly demanding "zero-carbon transportation" and "green supply chains", and green transportation will become a differentiating factor in market competition. Accumulating experience from demonstration projects and commercial operations can reduce risks and drive down loan, insurance, and financing costs. Collaboration between ship design stakeholders, shipyards, and

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manufacturers of fuel cells and hydrogen storage equipment will become closer to achieve scaled results.

Overall, within the next decade, it is highly likely that the hydrogen fuel cell main propulsion or hybrid propulsion will be commercialized for inland and coastal short-to-medium-distance container ships. For large ocean-going container ships to rely entirely on hydrogen power, major breakthroughs must be achieved in areas such as fuel cell service life, hydrogen storage volume and energy density, safety standards and supporting infrastructure.

7. Conclusions

Through the above review and analysis, the following conclusions can be drawn: The application of hydrogen power systems in container ships exhibits significant environmental and efficiency advantages as well as policy opportunities. Existing demonstration projects (with China's "Dongfang Qinggang" project as a typical example) have verified the feasibility of technology and system integration. However, key technical challenges—such as the optimization of hydrogen storage methods, the durability of PEMFC in harsh environments like salt spray, system integration and energy management, safety and regulatory standards, and cost issues—still need to be addressed through focused R&D and industrial collaboration.

To this end, the following suggestions are proposed to promote the development of hydrogen-powered container ships: (1) Policymakers should clarify green shipping goals and standards, and increase support for green hydrogen production, hydrogen refueling infrastructure construction, and the demonstration operation of fuel cell ships, including providing financial subsidies, tax incentives, and internalizing carbon emission costs. (2) Research institutions should prioritize research on the performance degradation mechanisms and recovery technologies of PEMFC in ship environments (such as salt spray, climate, and pollutants in supply air), as well as the corrosion resistance, pollution resistance, and long-term stability of key components such as electrodes, catalysts, membrane materials, and bipolar plates. (3) For hydrogen storage technology, efforts should be made to promote the practical application of lightweight high-pressure gas, liquid hydrogen, and LOHC technologies, and achieve breakthroughs in safety, volumetric density, insulation, and boil-off management. (4) Shipyards and shipping companies should participate in international and national demonstration projects, accumulate experience through commercial operations, verify the economic viability of technologies and systems, and improve the feasibility of insurance and financing. (5) International and regional maritime safety organizations and classification societies should formulate and promote mandatory safety standards and certification processes as soon as possible, covering fuel cell systems, hydrogen storage devices, refueling devices, safety monitoring, and emergency response.

If these measures are promoted in a systematic manner, hydrogen-powered container ships will advance from the demonstration stage to the stage of regular commercial application within 20–30 years, with inland and coastal routes taking the lead. The zero-carbon power goal for large ocean-going container ships is expected to become possible after the maturity of technologies, infrastructure, and market structures.

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