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Hydrogen-powered vessels in green maritime decarbonization: policy drivers, technological frontiers and challenges

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The global shipping industry is transitioning toward decarbonization, with hydrogen-powered vessels emerging as a key solution to meet international emission reduction targets, particularly the IMO's goal of reducing emissions by 50% by 2050. As a zero-emission fuel, hydrogen aligns with international regulations such as the IMO's greenhouse gas reduction strategy, the MARPOL Convention, and regional policies like the EU's Emissions Trading System. Despite regulatory support and advancements in hydrogen fuel cell technology, challenges remain in hydrogen storage, fuel cell integration, and operational safety. Currently, high-pressure gaseous hydrogen storage is the most viable option, but its spatial and safety limitations must be addressed. Alternative storage methods, including cryogenic liquid hydrogen, organic liquid hydrogen carriers, and metal hydride storage, hold potential for application but still face technical and integration barriers. Overcoming these challenges requires continued innovation in vessel design, fuel cell technology, and storage systems, supported by comprehensive safety standards and regulations. The successful commercialization of hydrogen-powered vessels will be instrumental in decarbonizing global shipping and achieving climate goals.

KEYWORDS

hydrogen-powered vessels, regulation, fuel cell technology, hydrogen storage, maritime decarbonization

1 Introduction

The global shipping industry is a significant contributor to carbon emissions, accounting for approximately 3% of global greenhouse gas emissions (Lindstad et al., 2011). With the growth of international trade, the carbon emissions of the shipping industry have increased, making its impact on climate change more significant (Bouman et al., 2017; Schwartz et al., 2020; Huang et al., 2025). International climate agreements, such as the Paris Agreement, have set emission reduction targets for the shipping sector (Bullock et al., 2024). Meanwhile, the International Maritime Organization (IMO) has established the "2050 Vision" goal, aiming to reduce the shipping industry's greenhouse gas emissions by 50% by 2050 (Serra and Fancello, 2020; Lindstad et al., 2023). However, reducing emissions in the shipping sector still faces challenges related to technological advancements, policy implementation, and global collaboration.

Currently, the core strategies for reducing emissions in the shipping industry focus on fuel transition, improving energy efficiency, and optimizing route management. Hydrogen, as a low-carbon and sustainable energy carrier, has gained increasing attention in recent years for its potential application in green shipping (Atilhan et al., 2021; Jesus et al., 2024). Hydrogen has a high energy density, and its combustion produces only water vapor with virtually no harmful emissions, making it an ideal alternative to traditional fossil fuels. In the shipping sector, hydrogen fuel cell-powered vessels have the potential to significantly reduce carbon dioxide and other pollutant emissions (Stark et al., 2022).

Despite the promising prospects of hydrogen in the shipping industry, several challenges remain, including the high costs of energy conversion and technical bottlenecks in hydrogen storage and transportation (Sürer and Arat, 2022; Fu et al., 2023). However, with the increasing capacity of renewable energy to produce green hydrogen, these obstacles are gradually being overcome. Additionally, continuous innovations in hydrogen storage and distribution systems, such as liquid hydrogen (Zheng et al., 2021; Yin et al., 2024) and solid-state hydrogen storage technologies (Xu et al., 2024; Kumar et al., 2022), are used to tackle technological problems. Policy support from the IMO and various national governments has also provided a strong impetus for the adoption of hydrogen in the shipping sector.

This article provides a comprehensive analysis of the development of hydrogen-powered vessels and explores their potential and practical applications as a green shipping solution. The objective is to examine the application of hydrogen technologies in ship propulsion systems, along with related technological innovations, regulatory developments, and industry standards. The article emphasizes the role of international and regional regulations in promoting the development of hydrogen-powered vessels, assesses their application practices and demonstration projects across different shipping sectors, addresses key technological breakthroughs, and analyzes the challenges encountered during the process of widespread adoption. Ultimately, this article aims to provide scientific evidence and development recommendations to support the broader implementation of hydrogen-powered vessels.

2 The influence of policy drivers on the development of hydrogen-powered vessels

Hydrogen-powered vessels play a crucial role in the low-carbon transition of the global shipping industry. With technological advancements, hydrogen fuel cells have become integral components of ship propulsion systems. Against the backdrop of global regulations increasingly influencing ship design, construction, and operation, IMO conventions and initiatives require reductions in carbon emissions, prompting countries to adopt stricter standards. Shipping companies must comply with these regulations, which provide both institutional and market support for the development of low-carbon technologies.

2.1 The regulatory framework of the international shipping industry and the urgency of decarbonization

The policies of the IMO in addressing climate change are significantly influenced by global climate agreements, particularly the Paris Agreement. The global temperature control targets set by the Paris Agreement have urged the IMO to take action on emission reductions in the shipping industry. As a major emitter of greenhouse gases, the shipping sector is directly impacted by the temperature control commitments of the Paris Agreement, and the IMO must ensure that the industry's emission reduction goals align with global climate targets (Franz et al., 2022; Martinez Romera, 2016).

The Greenhouse Gas (GHG) Reduction Strategy, developed by the IMO in 2018, aims to guide the global shipping industry in reducing greenhouse gas emissions in response to climate change. The core objective of the strategy is to achieve a reduction of at least 50% in GHG emissions from the shipping sector by 2050, compared to 2008 levels, and to strive for complete elimination of emissions where possible (Dewan and Godina, 2024). This target aligns with the global temperature control requirements of the Paris Agreement, ensuring that the shipping industry's emission reduction efforts are in harmony with global climate goals. The GHG strategy sets several phased reduction targets. One key task is to conduct a comprehensive review of existing emission reduction measures by 2023, in order to adjust relevant policies based on new technologies and market dynamics. By 2030, the goal is to reduce greenhouse gas emissions by 15-30%. Ultimately, by 2050, the global shipping industry must reduce its GHG emissions by 50% compared to the 2008 baseline. These goals will be progressively achieved through the promotion of clean energy utilization, green technology innovation, and international cooperation, supporting the transition of the shipping industry to a low-carbon future (Serra and Fancello, 2020). Although the GHG Reduction Strategy lacks direct legal binding force, it has established the regulatory direction for the IMO to formulate subsequent mandatory measures and voluntary guidelines.

The International Convention for the Prevention of Pollution from Ships (MARPOL) formulated by IMO is a mandatory international convention with legal binding force, aiming to prevent ships from polluting the marine environment (Xing, 2024; Van Roy et al., 2024). Since its establishment in 1973, MARPOL has undergone continuous revisions to adapt to evolving global environmental requirements, playing a significant role in reducing greenhouse gas emissions. The core objective of MARPOL is to mitigate the negative impacts of ship emissions on air, water bodies, and marine ecosystems, thereby promoting the green and sustainable development of the shipping industry. MARPOL includes multiple annexes, with the provisions concerning pollutant emission limits being particularly influential.

For example, Annex VI sets requirements for controlling air pollution from ships, covering emissions of sulfur, nitrogen oxides, and volatile organic compounds (Van Roy et al., 2023; SChinas and Stefanakos, 2014). Regarding sulfur emissions, MARPOL stipulates a global sulfur content limit of 0.5%, with stricter limits of 0.1% in specific control areas, such as Europe and North America. This encourages ships to use low-sulfur fuels or install exhaust gas cleaning systems (EGCS) (Zis and Cullinane, 2020; Winebrake et al., 2009). Additionally, nitrogen oxide emissions are restricted, requiring newly built ships to adopt highly efficient engine technologies. These provisions have raised environmental standards in the shipping industry, driving shipping companies to adopt innovative technologies, such as liquefied natural gas (LNG), as an alternative to traditional fuels, thereby contributing to global emission reductions in the shipping sector (Acciaro, 2014).

The MARPOL Annexes not only mitigate direct regional environmental pollution from ships through sulfur oxide and nitrogen oxide emission limits, but also propel the shipping industry's paradigm shift from 'end-of-pipe treatment' to 'source-driven design' via the implementation of the Energy Efficiency Design Index (EEDI). The EEDI is a key regulation established by the IMO to improve the energy efficiency of ships (Vasilev et al., 2024). This binding regulation establishes mandatory requirements for newly constructed ships to meet specific energy efficiency criteria during the design phase, thereby reducing greenhouse gas emissions generated throughout their operational lifecycle. Specifically, the EEDI measures the fuel consumption per unit of transport capacity (e.g., per ton of cargo) of a vessel, aiming to reduce energy consumption through technological innovation and optimized design. Emission standards and compliance requirements vary for different types of vessels due to differences in design and operational characteristics. Large cargo ships, such as oil tankers and container ships, face stricter EEDI standards, which typically require significant improvements over traditional design energy efficiency levels to address environmental impacts over long-term operations. Other types of vessels, such as bulk carriers and passenger ships, must also comply with corresponding standards based on their emission profiles. Vessels must adhere to the EEDI regulations and obtain compliance certification from an IMO-approved organization before construction (Issa et al., 2022). In 2021, the IMO incorporated the Energy Efficiency Existing Ship Index (EEXI) into MARPOL Annex VI as a new regulatory measure. The EEXI mandates that existing vessels implement technical modifications to achieve energy efficiency levels comparable to those required for newly built vessels under the EEDI framework (Bayraktar and Yuksel, 2023). This regulatory framework establishes complementary mechanisms: whereas the EEDI imposes carbon emission constraints at the design source for newly constructed vessels, the EEXI employs retroactive retrofitting measures to drive aging fleets toward clean propulsion technologies, notably hydrogen-based systems. These measures have driven the shipping industry toward a technological transition to low-carbon and energy-efficient solutions, aligning with global emission reduction targets.

Furthermore, the Global Shipping Climate Action Agenda (GSCAA), a multilateral initiative co-led by the Global Maritime Forum, the IMO and other stakeholders, encourages member states to strengthen international collaboration and advance technological research and development. Although the GSCAA operates as a non-binding voluntary initiative, it establishes an actionable framework with sector-specific technical guidelines to facilitate shipping companies' adoption of clean energy technologies. Through policy incentives and capacity-building programs, GSCAA enables the industry to achieve cost-effective compliance with environmental regulations while enhancing long-term economic viability.

The IMO has set a greenhouse gas reduction target for 2050, requiring the global shipping industry to achieve at least a 50% reduction in greenhouse gas emissions by that year. This target underscores the IMO's urgent response to global climate change and drives the shipping industry toward a low-carbon, sustainable transformation. To achieve this goal, the IMO has proposed a series of technological and policy solutions, including improvements in ship energy efficiency, the promotion of alternative fuel adoption, and the implementation of innovative environmental technologies. Among alternative energy technologies, hydrogen energy, as a zero-emission fuel, demonstrates great potential for use. Hydrogen can power vessels through hydrogen fuel cells or internal combustion engines, thereby avoiding the carbon dioxide and other greenhouse gases produced by burning fossil fuels. Compared to conventional fuels, the application of hydrogen can not only effectively reduce emissions but also contribute to the transformation of the shipping industry's energy structure, thus reducing dependence on petroleum resources.

2.2 The influence of regional regulations and policies on the hydrogen-powered ship industry

Regional regulations and policies in the shipping industry form a critical component of global environmental and emission reduction strategies, with a focus on addressing the unique environmental challenges of each region. Europe, Asia, and North America, among other regions, have implemented stringent emission standards and fuel requirements to drive the shipping industry toward a low-carbon and greener future.

The European Union's green shipping policies reflect its strong commitment to addressing global climate challenges. As a pioneer in environmental protection, the EU has implemented stringent regulations and policies to drive the shipping industry's green transformation and reduce carbon emissions, while also supporting the development and application of emerging green technologies. The EU Climate Law sets a "climate-neutral" target for 2050, requiring member states to make significant emissions reductions. As a major source of carbon emissions within the EU, the shipping industry must contribute to this goal (Montanarella and Panagos, 2021; Kulovesi et al., 2024). The Climate Law provides policy guidance for the sector, specifying that emissions must be significantly reduced between 2030 and 2050. To achieve this, the EU has also implemented the Emissions Trading System (ETS), which economically encourages shipping companies to accelerate the adoption of low-carbon technologies, improve energy efficiency, and invest in alternative fuels (Li et al., 2019; Fageda and Teixidó, 2022). Hydrogen, as a zero-emission fuel, shows tremendous potential in long-distance and heavy-duty shipping, making it a focal point of the EU's green shipping policy. Through initiatives like the Horizon Europe program, the EU provides funding to encourage the adoption of hydrogen-based solutions in the shipping industry, advancing research into key technologies such as hydrogen fuel cells and liquid hydrogen storage. The EU also promotes the commercialization of green hydrogen technologies. Additionally, demonstration projects like Hydro-Assist offer technical solutions, assisting in the development of innovative hydrogen-powered vessels and facilities, promoting the hydrogen supply chain and infrastructure, and accelerating the low-carbon transformation of the shipping industry.

Japan, South Korea and China have adopted proactive policy measures in the development of hydrogen-powered vessels, demonstrating their commitment to addressing climate change and driving the green transformation of the shipping industry. These countries are taking a multidimensional approach to policy, vigorously promoting the application of hydrogen technologies, with the aim of gaining a competitive edge in the global green transformation of the shipping industry. As a pioneer in hydrogen-powered vessel development, Japan is actively advancing the application of hydrogen in the shipping sector under its hydrogen society promotion strategy (Yap and McLellan, 2024; Chaube et al., 2020). The government of Japan provides research and development subsidies, project funding, and tax incentives to support the design and construction of hydrogen fuel cell vessels. Additionally, Japan fosters public-private partnerships through initiatives like the hydrogen fuel cell ship demonstration program, exemplified by the "Energy Observer" and "Fuji Maru" projects, which facilitate the verification and commercialization of green technologies. Furthermore, Japan is accelerating the development of hydrogen infrastructure, constructing systems for the production, storage, and transportation of liquid hydrogen, with steady progress in building the hydrogen supply chain for port facilities, laying the foundation for the operation of hydrogen-powered vessels.

South Korea has also set ambitious strategies for hydrogen-powered vessels. Its Green New Deal aims to position the country as a global leader in hydrogen technology by 2030, with the low-carbon transformation of the shipping industry being a key component (Lee and Woo, 2020; Han and Lee, 2023). The government provides funding support for the research and development of hydrogen-powered vessels and has established dedicated institutions, such as the Korea Hydrogen Institute, to drive technological breakthroughs in hydrogen storage and fuel cells. Leveraging its leadership in the shipbuilding industry, South Korea guides shipbuilding companies through industrial policies to develop hydrogen-powered vessels, while stimulating investments in the hydrogen sector through financial subsidies, tax reductions, and green financing policies. Moreover, South Korea has made significant progress in building hydrogen infrastructure, with several ports actively advancing the construction of hydrogen storage facilities, contributing to the commercialization of hydrogen-powered vessels.

China has also implemented far-reaching measures in the development of hydrogen-powered vessels. The Chinese government has explicitly included the green transformation of the shipping industry in its "14th Five-Year Plan and Vision for 2035" promoting the innovation of green, low-carbon technologies (Zhang et al., 2022; Hepburn et al., 2021). The government offers substantial financial support for the research and development of hydrogen technologies, particularly in hydrogen fuel cells and hydrogen storage and transportation technologies, fostering an innovation mechanism that involves both government guidance and corporate collaboration. Additionally, the government has established special funds and subsidies to support the industrialization of hydrogen-powered vessels. China's port infrastructure is gradually transitioning to accommodate hydrogen energy, with several ports beginning to build hydrogen storage and refueling facilities, providing solid support for the operation of hydrogen-powered vessels.

The United States adopts a dual approach of policy support and market-driven incentives to invest in hydrogen technology and achieve low-carbon goals in the shipping industry. The U.S. government has implemented a range of strategies and funding initiatives to accelerate the development and application of hydrogen technologies in the maritime sector. The U.S. Department of Energy's Hydrogen and Fuel Cell Technology Strategic Plan outlines large-scale investments to accelerate the commercialization of hydrogen, covering research and development across the entire hydrogen value chain (Miller et al., 2020; Garland et al., 2012; Bade and Tomomewo, 2024). Additionally, the government uses subsidy-based incentive mechanisms to encourage shipping companies to adopt hydrogen, particularly in the design, construction, and operation of green vessels. Faced with pressures to reduce carbon emissions and enhance energy efficiency, the U.S. Environmental Protection Agency and the Coast Guard have set stringent emission standards to drive the shipping industry toward a clean energy transition. The "Clean Power Plan" approved in 2015, includes the shipping sector within its carbon reduction framework, with hydrogen as a key zero-emission energy source. Regional environmental regulations further accelerate the application of hydrogen-powered vessels. Emission Control Areas (ECAs) and stringent carbon regulations in regions like California have prompted the shipping industry to explore low-carbon technologies (Vutukuru and Dabdub, 2008; Lurmann et al., 2014). California, in collaboration with the Maritime Commission, promotes technology research and provides funding and policy support for hydrogen vessel pilot projects. Meanwhile, U.S. ports and companies are actively constructing hydrogen infrastructure to facilitate the widespread adoption of hydrogen-powered vessels. Guided by regional regulations, the U.S. shipping industry's application of hydrogen energy is gradually becoming market-driven, solidifying the policy and technological foundation for a low-carbon transformation.

Collectively, global and region-specific environmental regulations are driving the shipping industry toward low-carbon and environmentally sustainable development. These regulatory frameworks not only mandate emission reductions but also provide policy incentives to accelerate the adoption of hydrogen-based technologies, thereby catalyzing design innovations in hydrogen-powered vessels. It can be argued that shipping regulations and incentive policies have significantly catalyzed reforms and innovations in hydrogen-powered vessels across design, manufacturing, and safety governance. Fuel cell systems are core technologies for hydrogen-powered vessels, and the stringent carbon emission and air pollution requirements set by the IMO and governments have accelerated their development. Meanwhile, these regulatory frameworks have further compelled naval architects to innovate in vessel structural design, material selection, and hydrogen storage technologies, exemplified by optimized hydrogen storage compartment layouts, novel cryogenic storage solutions, and energy-efficient spatial configurations that simultaneously enhance cargo capacity. Furthermore, global and region-specific environmental mandates have prompted the IMO and national maritime authorities to develop specialized regulatory guidelines for hydrogen-powered shipping. These guidelines codify safety standards for hydrogen storage, transportation, and onboard utilization, driving the sector toward safer, more efficient, and environmentally sustainable development trajectories.

3 The development of hydrogen-powered vessels

The previous section examined the IMO's emissions regulations for the shipping industry, along with the policy drivers of various nations. These regulations and policies not only reflect the global commitment to environmental protection and greenhouse gas reduction but also provide a clear direction and framework for the green transformation of the shipping industry. The shipping sector is facing unprecedented challenges and opportunities, and hydrogen energy, as one of the representative clean energy sources, has become a focal point for the industry's attention in terms of its application in ship propulsion systems. Currently, numerous hydrogen-powered vessel projects around the world are either operational or in the testing phase, signaling that the application of hydrogen in the maritime sector is gradually transitioning from theory to practice.

3.1 Typical case studies of hydrogen-powered vessels

The application of hydrogen-powered vessels in the maritime industry has garnered widespread attention, representing a significant step toward reducing carbon emissions and promoting sustainable shipping practices. After decades of research and development, hydrogen-powered ship technology has achieved several key breakthroughs, laying a solid foundation for the advancement of green maritime technologies. This article explores key applications of hydrogen-powered vessels, summarized in Table 1, analyzing their technological background, operational

TABLE 1 Typical hydrogen fuel-powered vessels in the world.

Vessel Name	Country	Power Type	Key Technical Features	Application Scenarios
212A Submarine	Germany	PEMFC (306kW)	Metal Hydride Hydrogen Storage, Double-Hull Safety Design	Military AIP Submarine
Viking Lady	Norway	LNG Fuel Cell (320kW)	Hybrid Power Architecture, Long-Term Operation in the North Sea	Engineering Vessel
Energy Observer	France	PEMFC (60kW) + Solar/Electrolysis	Energy Self-Sufficiency, Onboard Hydrogen Production	Scientific Research and Demonstration Vessel
SF-BREEZE Ferry	the United States	PEMFC (2,400kW)	Liquid Hydrogen High-Vacuum Storage Tank, Adapted for Scientific Research	Underwater Sample Collection Vessel
Lihu	China	PEMFC (70kW) + Lithium Battery	First Domestic Fuel Cell Yacht	Inland Leisure Yacht
Ulstein SX190	Norway	PEMFC (7.5MW) + Lithium Battery	Fully Electric Drive, Containerized Hydrogen Storage	Offshore Engineering Vessel
Three Gorges Hydrogen Boat No. 1	China	PEMFC (500kW)	Inland Green Hydrogen Refueling, Steel-Aluminum Composite Hull	Inland Freight Ferry
Topeka	Norway	PEMFC (3MW) + LH2 Storage	Hydrogen Transport + Cargo Dual-Function Platform	Liquid Hydrogen Transport Vessel

Source: Created by this Research.

success, and role in driving sustainable development in the maritime industry.

The application of hydrogen technology in ships dates back to the 1980s when the German Navy began equipping its submarines with proton exchange membrane fuel cells (PEMFCs) provided by Siemens. In 1990, the HDW company retrofitted the Type 209/1200 submarine and successfully developed the world's first hydrogen-oxygen fuel cell-powered submarine—the 212A model with air-independent propulsion (AIP) (Psoma and Sattler, 2002). This submarine could operate underwater for extended periods without relying on surface oxygen, laying the foundation for the future development of hydrogen-powered ship technologies and demonstrating the feasibility of using hydrogen in confined, high-performance environments.

As technology advanced, a significant milestone for hydrogen-powered vessels was reached in 2009 when the "Viking Lady" became the world's first ship to be equipped with a 320 kW LNG fuel cell power system (Vairo et al., 2023). The ship operated continuously in the North Sea for over 18,500 hours, marking a groundbreaking advancement in marine power systems and paving the way for the further development of hydrogen-powered vessels. In 2015, the "Viking Lady" participated as a clean energy demonstration vessel at the Copenhagen Climate Summit, showcasing its ability to transition from traditional energy to new energy and serving as a significant symbol of the evolution of maritime environmental protection technologies (Issa et al., 2022). This achievement not only demonstrated the technical feasibility of hydrogen fuel cells in ships but also fueled global interest in sustainable maritime technologies.

Following the "Viking Lady", France's "Energy Observer", launched in 2017, became the world's first self-sufficient hydrogen-powered vessel (Wang et al., 2024b; Gambini et al., 2024). This ship integrates solar power, wind energy, and seawater electrolysis for hydrogen production, utilizing a Toyota Mirai hydrogen fuel cell system to achieve zero carbon emissions. Through this innovative application, the "Energy Observer" has demonstrated the immense potential of combining hydrogen with renewable energy. It not only operates with zero emissions but also serves as a significant symbol of the maritime industry's transition to clean energy. The vessel's successful operation has proven the sustainability of hydrogen as a propulsion source and provided valuable practical experience for the development of future zero-emission ships.

In 2021, the U.S. Sandia National Laboratories launched the Zero-Emission Hydrogen Fuel Cell Ferry Project, aiming to reduce carbon emissions in ferry operations by utilizing a dual 300 kW electric propulsion system (Chavan et al., 2023). The 21-meter ferry was designed for research tasks, such as underwater sample collection in San Francisco Bay. The project utilized 20 stacks of 4×30 kW proton exchange membrane fuel cells and employed high-vacuum insulated technology for hydrogen storage, allowing the ship to travel approximately 185 kilometers per refueling of liquid hydrogen (Di Ilio et al., 2024). With its independent double-hull structure and forced ventilation system, this ferry can safely control hydrogen concentration. This project highlights the broad application prospects of hydrogen fuel cells in scientific research and public transportation, demonstrating the potential of hydrogen technology in specialized environments.

China has also made significant progress in hydrogen-powered ship technology. In 2021, China's first fuel cell-powered yacht, "Lihu" was completed (Wang et al., 2023). Developed by Dalian Maritime University, the yacht is equipped with a 70 kW fuel cell and an 86 kWh lithium battery hybrid power system, with a design speed of 18 km/h and a range of 180 kilometers, capable of carrying 10 passengers. As a milestone in China's fuel cell ship sector, the "Lihu" not only validates the feasibility of hydrogen-powered ships but also provides a green technological pathway for yachts and other high-experience vessels. The smooth performance and low noise characteristics during trials demonstrate the tremendous potential of hydrogen as a clean energy propulsion system in ships, especially in luxury yachts and the high-end market.

In 2023, the Norwegian Ulstein Group completed the hydrogen-powered offshore engineering vessel Ulstein SX190, equipped with a 2 MW hydrogen fuel cell system provided by Nedstack as its main power source, delivering a total power of 7.5 MW (Wang et al., 2024b; Bagherabadi et al., 2023). This vessel can operate in "zero-emission mode" for up to four days, with the potential to extend this to two weeks through technological upgrades. The ship's innovation lies in its use of a containerized hydrogen storage solution, which stores hydrogen in standard shipping containers, making global transportation and reuse more convenient. This innovative design is of great significance for offshore engineering vessels, particularly for complex offshore operations such as deep-sea and offshore energy development, where hydrogen can effectively reduce the use of traditional fuels and carbon emissions.

Following that, in October 2023, China's first hydrogen fuel cell-powered demonstration vessel, the "Three Gorges Hydrogen Boat No. 1" completed its maiden voyage in Hubei Province, marking a breakthrough for hydrogen technology in China's inland waterway shipping sector (Guan et al., 2023, 2024). Developed by the Three Gorges Corporation in collaboration with multiple partners, the ship has a total length of 49.9 meters, is powered by a 500 kW hydrogen fuel cell system, and has a maximum speed of 28 km/h and a range of 200 kilometers, achieving zero carbon emissions. The vessel is supported by China's first inland hydrogen refueling station, which utilizes green electricity from the Three Gorges to produce hydrogen, replacing 103 tons of fuel annually and reducing carbon dioxide emissions by 345 tons. As China's first hydrogen-powered demonstration vessel for inland waterways, the "Three Gorges Hydrogen Boat No. 1" not only showcases the potential of hydrogen in China's inland shipping but also promotes the development of the green hydrogen industry.

In Europe, the "Topeka" ship is a key vessel in the hydrogen-powered ships project. It uses liquid hydrogen (LH2) and proton exchange membrane fuel cell technology, equipped with a 1 MWh battery pack and a 3 MW fuel cell system to achieve zero carbon emissions (Ustolin et al., 2022; Panić et al., 2022). Operated by the Norwegian Wilson Group, the ship is expected to enter commercial service in 2024, transporting liquid hydrogen and road freight along Norway's western coast. Its innovative design features a "dual-purpose" transport model, serving both as a coastal cargo ship and a hub for liquid hydrogen container refueling. This design aims to address one of the significant challenges in the promotion of hydrogen-powered ships: the shortage of refueling infrastructure. Such an initiative lays the foundation for the development of a liquid hydrogen marine transportation ecosystem. The existence of the "Topeka" is expected to greatly reduce the need for approximately 25,000 truck trips annually and provide a sustainable solution for hydrogen and freight transportation in the region.

In conclusion, these application cases demonstrate the significant impact of hydrogen-powered vessels across various types of ships, including submarines, ferries, yachts, offshore engineering vessels, and cargo ships. They highlight the versatility of hydrogen as a clean energy source and emphasize its broad potential for the maritime industry. The integration of hydrogen fuel cells with renewable energy sources such as solar, wind, and electrolysis opens up new possibilities for achieving zero-emission shipping. The operational experiences of these pioneering vessels provide valuable case studies on the technical challenges and development opportunities in the widespread adoption of hydrogen-powered ships. With ongoing technological advancements and growing global interest in sustainable shipping, the future of hydrogen-powered vessels looks promising. However, further research, investment in infrastructure, and regulatory support are essential to fully realize hydrogen's potential as the cornerstone of the maritime industry's transition to a low-carbon future.

3.2 Technical standards and safety specifications for hydrogen-powered vessels

Since 2021, the IMO has published interim guidelines for the safety of ships using fuel cell power installations, marking the first comprehensive global guideline addressing the safety of hydrogen fuel cell vessels (Inal, 2024). These guidelines detail technical standards for key aspects of fuel cell-powered systems in ship design, layout, material selection, fuel storage and refueling, electrical equipment configuration, emergency response, and more. They emphasize hydrogen leak prevention, the use of inert environments, and compatibility requirements between the fuel cell system and the ship's electrical system. The core objective is to establish safety management protocols for the entire lifecycle of hydrogen fuel cell vessels, effectively reducing risks such as fires and explosions, while also providing a solid practical foundation for the IMO to develop more stringent mandatory regulations in the future.

Internationally, DNV GL (Norwegian Classification Society) partnered with 26 industry stakeholders in July 2021 to release the groundbreaking handbook for hydrogen-fuelled vessels (Klebanoff et al., 2021; Li et al., 2024b), which focuses on PEMFCs, elaborates on the design, construction, and risk assessment processes for hydrogen systems. It comprehensively covers key areas such as hydrogen storage, refueling, and leak prevention, while also providing customized solutions for the unique offshore operational environment. The second phase of the manual will focus on experimental research and the standardization of cryogenic liquid hydrogen, aiming to drive the ongoing updates and technological iterations of the manual.

The American Bureau of Shipping (ABS) has played a proactive role in supporting the decarbonization of the maritime industry. ABS has systematically outlined the applications of hydrogen fuel cell technologies and published two pivotal documents. The guide for fuel cell power systems for marine and offshore applications not only highlights the multiple advantages of fuel cell technology but also emphasizes the tremendous potential of combining Solid Oxide Fuel Cells (SOFC) with gas turbine hybrid power systems to significantly reduce carbon emissions across the entire lifecycle of ships (Xing et al., 2021). Additionally, the ABS white paper series outlines a "three-phase" decarbonization plan: focusing on energy efficiency improvements in the short term, accelerating the adoption of transitional fuels such as methanol and ammonia in the medium term, and relying on the deep integration of hydrogen energy and carbon cycle technologies in the long term.

The Bureau Veritas (BV) launched the guidelines for fuel cell systems onboard commercial ships, which provide a detailed technical specification and safety framework for the application of fuel cell power systems in commercial vessels. These guidelines stipulate that fuel cell systems must be deeply integrated into the overall energy architecture of ships, while also supporting the use of biodiesel and biogas as backup fuels to ensure ships can safely return to port in emergencies.

In 2023, Lloyd's Register (LR) published the hydrogen fuel-powered vessel design code (Appendix LR3), which further clarifies the safety requirements for hydrogen fuel cell systems.It covers core elements such as leak scenario analysis and refueling station layout. The code has already been successfully applied to the hydrogen-powered ferry project in Norway, which is planned to be launched in 2025.

In 2024, the Nippon Kaiji Kyokai (NK) updated its guidelines for the use of alternative fuels for ships by adding hydrogen energy-related content. The guidelines emphasize the prevention of explosions and the potential environmental impact of hydrogen leaks. NK also granted approval in principle for the design of the world's first liquid hydrogen fuel tanker, which integrates hydrogen fuel cell technology with Yanmar engines. This showcases Japan's leadership in hydrogen-powered vessel design (Chavando et al., 2024).

The Korean Register (KR) has focused on the safety of hydrogen refueling operations for vessels and released the Hydrogen Fuel Vessel Safety Refueling Operation Guidelines, which cover refueling standards for gaseous, liquid, and solid hydrogen. KR is also actively promoting the international standardization of hydrogen fuel cell-powered vessel technologies.

Since 2015, the China Classification Society (CCS), in close collaboration with the China Maritime Safety Administration (CMSA), has made significant contributions to the development of the standard system for marine fuel cell technologies. In 2021, CCS released the guidelines for ship applications of fuel cell power plants, which systematically outline the technical standards across ten core chapters related to ship design, layout, fuel storage, and electrical equipment. This was the first time that the guidelines introduced an additional certification mechanism. Subsequently, in March 2022, the interim rules for the technology and inspection of hydrogen fuel cell-powered vessels were implemented, further refining requirements for hydrogen storage, refueling, and fuel cell system integration. These rules clearly establish technical verification procedures when hydrogen fuel cells are used as the primary propulsion power.

Regulatory guidelines and standards for hydrogen-powered vessels are listed in Table 2. Various classification societies and international organizations have made significant achievements in developing regulations and guidelines for hydrogen-powered vessels. These regulations and guidelines not only establish a robust framework for the safety and reliability of hydrogen vessels but also provide strong support for the shipping industry's green and low-carbon transformation. With the continuous advancement of hydrogen technologies, the gradual reduction in costs, and the growing global focus on environmental protection and sustainable development, hydrogen-powered vessels will undoubtedly play an increasingly important role in the future of the maritime industry and make a substantial contribution to the global green transformation of shipping.

4 Hydrogen storage technology in hydrogen-powered vessels

Although fuel cell systems serve as the core power supply for hydrogen-powered vessels, safety is undoubtedly the primary consideration when evaluating the unique environmental conditions of vessel operations. Therefore, ensuring operational safety while meeting the vessel's range requirements has become a key issue that must be addressed. Hydrogen storage technology, which bridges the fuel cell system and the vessel's range capability, is extremely important. The level of development of this technology will determine the future application of hydrogen-powered vessels. Thus, hydrogen storage technology is a critical issue to address, and any breakthroughs in this area will have a profound impact on the entire hydrogen vessel industry.

High-pressure gaseous hydrogen storage technology, characterized by its established technical maturity, currently serves as the predominant storage methodology implemented in hydrogen fuel cell propulsion systems for marine vessels (Zhang and Jiang, 2023). Existing hydrogen fuel cell-powered ships, such as the "Lihu" and "Three Gorges Hydrogen Boat No.1" predominantly utilize this technology, with storage pressures around 35 MPa. However, high-pressure gaseous hydrogen storage faces significant spatial and safety challenges. Specifically, its low volumetric energy density requires substantial onboard space for hydrogen storage, which adversely impacts the vessel's spatial configuration. For example, compressed hydrogen gas at 35 MPa has a volumetric energy density approximately one-tenth that of marine diesel, with the storage tanks occupying several times the volume of conventional fuel tanks (Van Hoecke et al., 2021; Xie et al., 2024). Additionally, due to hydrogen's low density and high diffusivity, safety considerations prevent placing high-pressure hydrogen storage tanks in the ship's lower holds. As a result, they are typically mounted on the deck when connected to the vessel's systems. To address these challenges, several measures are being considered (Ma et al., 2024). First, optimize the design of hydrogen storage tanks to enhance their volumetric efficiency, thereby reducing the required storage volume. Second, advancements in materials science, such as the development of lightweight and high-strength composite materials for storage tanks, can decrease weight while maintaining structural integrity. Third, integrate advanced insulation and temperature control systems to manage the thermal characteristics of hydrogen and ensure safe and efficient storage. By implementing these design improvements, space and weight factors can be used more efficiently, thereby enhancing the overall performance and safety of hydrogen-powered vessels. In summary, while high-pressure gaseous hydrogen storage technology offers a viable pathway for the adoption of fuel cell-powered vessels, it is crucial to overcome the associated spatial and safety challenges. Ongoing research and technological advancements are essential to optimize storage solutions and ensure the practicality and safety of hydrogen as a marine fuel.

The development of cryogenic liquid hydrogen storage technology in the field of hydrogen-powered vessels is still in the exploratory stage. However, it has demonstrated significant promise for the future (Ustolin et al., 2022; Van Hoecke et al., 2021; Li et al., 2022). Currently, the main challenges of this technology include maintaining the ultra-low temperature environment of -253°C and ensuring effective insulation, which impose stringent requirements on material performance and system integration (Zhang and Jiang, 2023). In Europe, cross-sector collaborations are accelerating technological breakthroughs. Regarding technological bottlenecks, liquid hydrogen storage tanks are costly and present thermal management challenges. Additionally, the frequent refueling requirements during vessel operations and the inadequate compatibility with existing hydrogen refueling infrastructure hinder large-scale adoption. The IMO is proactively enhancing safety codes for liquid hydrogen, thereby establishing a robust regulatory framework to ensure the safe operation of liquid hydrogen carriers. In the future, with the advancement of EU-funded projects like the "Clean Hydrogen Partnership" liquid hydrogen storage technology is expected to achieve breakthroughs in the deep-sea vessel sector (Vivanco-Martin and Iranzo, 2023). Its high energy density will significantly enhance the endurance of long-range vessels, making it a key solution for global shipping decarbonization.

Organic Liquid Hydrogen Carrier (LOHC) technology is currently undergoing technical validation and demonstration in the field of hydrogen-powered vessels. Its core advantages include safe storage and transportation under ambient temperature and pressure, high hydrogen storage density, and recyclability (Teichmann et al., 2012; Preuster et al., 2017; Noh et al., 2023). In

TABLE 2 Regulatory guidelines and standards for hydrogen-powered vessels.

Issuing Authority	Field	Release Date	Main Contents	Technical Highlights
IMO	Interim Guidelines for the Safety of Ships Using Fuel Cells	2021	First global framework addressing hydrogen fuel cell safety, covering design, arrangement, material selection, hydrogen storage/loading, electrical systems, and emergency management. PROVIDED a basis for future mandatory regulations.	Emphasized hydrogen leakage control, inert atmosphere requirements, and integration with shipboard power systems.
DNV	Handbook for Hydrogen-Fuelled Vessels	2021	Systematic guidelines for hydrogen-fuelled ship design, construction, and risk assessment, focusing on PEMFC technology and marine environmental adaptability.	Addressed hydrogen's physical properties (lightweight, high diffusibility) and introduced risk-based safety assessments.
ABS	Guide for Fuel Cell Power Systems in Marine and Offshore Applications	2021	Defined hydrogen fuel cell advantages (40%-60% energy efficiency, zero emissions) and proposed SOFC-gas turbine hybrid systems for decarbonization.	Highlighted three-stage decarbonization strategy: energy efficiency (short-term), transitional fuels (medium-term), and hydrogen-carbon cycle (long-term). Predicted hydrogen to account for 30% of marine energy by 2050.
ABS	SETTING THE COURSE TO LOW CARBON SHIPPING: 2030 Outlook 2050 Vision	2021	Outlined hydrogen as a transitional fuel alongside green hydrogen for zero-carbon shipping.	Emphasized hydrogen storage, bunkering infrastructure, and certification standards.
BV	Guidelines for Fuel Cell Systems Onboard Commercial Ships	2021	Required deep integration of fuel cell systems with ship energy architectures, supporting dual-fuel compatibility (e.g., biodiesel, biogas).	Mandated hydrogen storage safety standards, heat recovery systems, and compliance with SOLAS/MARPOL conventions.
LR	Hydrogen Fuelled Ships Design Code (Appendix LR3)	2023	Established safety requirements for hydrogen fuel cell systems, including leak scenarios, bunker station layouts, and lifecycle management.	Validated for Norwegian hydrogen-powered ferry projects (2025 launch).
JMSA	Guidelines for Alternative Fuel Ships (2024 Update)	2024	Added hydrogen-specific requirements, emphasizing leak prevention and safe return-to-port (SRtP) capabilities. Granted AiP to the world's first liquid hydrogen tanker.	Proposed hybrid systems (fuel cells + Wärtsilä engines) and ammonia transition strategies.
KR	Hydrogen Fuel Safety Bunkering Operations Guidelines	2024	Standardized gaseous, liquid, and solid hydrogen bunkering procedures, aligning with international standards.	Focused on standardized operations and safety protocols for global hydrogen supply chains.
CCS	Guidelines for Alternative Fuel Ships	2017	First Chinese framework incorporating hydrogen fuel cells, outlining basic safety requirements.	Laid foundational standards for China's hydrogen ship sector.
CCS	Guidelines for Fuel Cell Power Generation Systems on Board Ships	2021	Detailed technical specifications for hydrogen fuel cell ships, including design, layout, storage, and electrical systems. Introduced optional certification marks.	Specified hydrogen storage, bunkering, and system integration standards.
CCS	Interim Rules for Hydrogen Fuel Cell-Powered Ships (2022)	2022	Formalized hydrogen fuel cells as primary propulsion systems, clarifying technical validation and environmental compliance.	Established mandatory inspection procedures for hydrogen fuel cell systems.
CCS	Product Inspection Guidelines for Hydrogen Fuel Cells, Hydrogen Tanks, and Reformers (2022)	2022	Set validation criteria for key components (e.g., PEMFC durability [-20°C to 60°C], hydrogen tank safety valves, reformer efficiency).	Fulfilled technical gaps in domestic hydrogen ship standards; ensured compliance with international norms (SOLAS/MARPOL).

Source: Created by this Research.

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China, the China Shipbuilding Industry Corporation's 712 Research Institute has developed a 40 kW LOHC hydrogen supply module prototype. This system integrates catalytic combustion heating with a combined reactor design, and its 120 kW-class device has been matched with a fuel cell system for hydrogen supply. Currently, LOHC technology faces several challenges, including high dehydrogenation energy consumption, catalyst deactivation due to side reactions, and concerns about its economic feasibility. The full-process cost of LOHC is still 30%-50% higher than that of high-pressure gaseous hydrogen storage. Vessels also have stringent requirements for hydrogen storage density and endurance (Foisal, 2023; Li et al., 2024a). LOHC offers a volumetric hydrogen density of up to 71 kg/m^3, and can utilize existing oil product transportation networks for long-distance refueling, making it suitable for ocean-going vessels. However, space limitations on vessels necessitate highly integrated storage systems, and LOHC technology is currently in the auxiliary verification stage.

Metal hydride hydrogen storage technology is currently in the exploratory phase of application within the hydrogen-powered maritime sector, yet it has demonstrated notable technical potential and distinct advantages (von Colbe et al., 2019; Lazar et al., 2023; Chung et al., 2015). Traditional hydrogen-powered vessels predominantly utilize high-pressure gaseous hydrogen storage systems, operating at pressures such as 35 MPa or 70 MPa, which suffice for short to medium-range maritime operations. However, these systems have substantial volume and weight, posing challenges for long-haul vessels that require lightweight and extended-range solutions. Metal hydride storage technology emerges as a promising alternative due to its high energy density and the capability for safe storage at ambient temperature and pressure. Nonetheless, several technical challenges impede the widespread adoption of metal hydride storage in maritime applications. The cycle life of metal hydride systems is approximately 2,000 cycles, which is shorter compared to the 5,000 cycles achievable by high-pressure gaseous systems. Additionally, large-scale implementation necessitates addressing engineering challenges related to hydrogen purity control and the integration of storage systems. Advancements in metal hydride storage technology, particularly in enhancing cycle life and system integration, are essential to fully realizing their potential in hydrogen-powered vessels. Addressing these challenges will significantly influence the future landscape of sustainable maritime transportation.

The hydrogen storage technology for hydrogen-powered vessels is critical to the industry's development and involves several competing methods, each with distinct advantages and challenges. High-pressure gaseous hydrogen storage technology, widely adopted in short-to medium-range vessels, is the most mature and commercially viable option. It provides a practical solution with storage pressures, though it presents spatial and safety challenges due to its low volumetric energy density and the significant space required for storage tanks. To improve efficiency, research is focusing on optimizing tank design, using lightweight materials, and enhancing insulation systems. Cryogenic liquid hydrogen storage technology offers higher energy density but is still in the exploratory phase. Its primary challenges include maintaining the ultra-low temperature of -253°C, which requires advanced insulation and energy management systems. Despite these difficulties, liquid hydrogen's capability of greatly enhancing the range of long-distance vessels makes it a promising fuel for future development. LOHC technology, which allows hydrogen storage under ambient conditions, is also advancing. While it offers high storage density and recyclability, it faces difficulties related to high dehydrogenation energy consumption and catalyst costs. LOHC technology is not yet commercially viable on a large scale but may be a key component for future long-range maritime applications. Metal hydride storage, with its potential for high energy density and safe operation at ambient temperature and pressure, offers another alternative. However, it is constrained by cycle life limitations and integration challenges. As research continues, breakthroughs in these storage technologies will play a crucial role in the widespread adoption of hydrogen-powered vessels and enable the shipping industry's transition to low-carbon and sustainable operations.

5 Hydrogen-powered vessels: challenges and prospects

Amidst the global imperative for maritime decarbonization, hydrogen-powered vessels have been incorporated into zero-carbon strategic frameworks across nations as a pivotal solution, with policymakers explicitly articulating long-term visions for commercial fleet deployment. However, technology readiness assessments reveal that the large-scale adoption of hydrogen propulsion systems faces persistent barriers. Achieving scalable implementation necessitates dynamic synergy between policy interventions and technological advancements to address these systemic challenges.

5.1 Challenges faced by hydrogen-powered vessels

Despite the widespread promotion of the hydrogen energy industry in recent years and significant development in hydrogen fuel cell technology, green hydrogen production methods, and hydrogen storage and refueling technologies, the application of hydrogen fuel-powered systems in the maritime sector still has numerous areas that require further research and development. These areas include, but are not limited to, safety concerns regarding hydrogen fuel, cost-effectiveness considerations, insufficient infrastructure, and the need for improvement in relevant regulations and standards. These challenges not only prevent the commercialization of hydrogen-powered vessels but also require interdisciplinary collaboration and technological innovation to address them.

5.1.1 Challenges in the development of safety standards and technical regulations for hydrogen-powered vessels

Hydrogen-powered vessels, as a key technological solution for achieving carbon neutrality in the shipping industry, face significant challenges in their commercialization process due to the inadequacy of safety regulations and technical standards. The existing standard system exhibits notable structural flaws, as outlined in the following aspects:

Disjointed Technical Standards System: Current hydrogen energy standards for maritime vessels remain embedded within land-based regulatory frameworks (Wang et al., 2024b). While the IMO has issued preliminary guidelines for hydrogen fuel safety, key technical parameters continue to lag behind evolving technological requirements (Hoang et al., 2023; Petrychenko et al., 2025). For instance, shipboard fuel cell systems require power capacities in the hundreds of kilowatts, which far exceed the requirements for automotive systems. However, core parameters such as battery consistency and heat dissipation design still lack specific regulations. Regarding hydrogen storage systems, no established standards exist for key aspects such as the installation of 70 MPa high-pressure gas cylinders on vessels or specifications for metal hydride hydrogen storage technology (Hoang et al., 2023), resulting in mismatches between hydrogen storage capacity and the operational range of ships.

Delayed Refueling and Supply Systems: Currently, only a few ports have initiated pilot hydrogen refueling facilities (Hoang et al., 2023), substantially limiting the operational scope of hydrogen-powered vessels. Moreover, the lack of globally harmonized standards for hydrogen bunkering technologies and infrastructure (Bortnowska and Zmuda, 2024)—such as pressure ratings for storage tanks, bunkering interface specifications, liquid hydrogen transfer rates, safety distance requirements, and operational protocols (Van Hoecke et al., 2021)—has created interoperability challenges for transoceanic shipping. This necessitates compatibility with multiple systems, incurring additional economic and temporal costs.

Multiple Safety Management Gaps: Current standards do not quantify scenarios such as hydrogen leakage diffusion simulations or crew emergency protection. While the IMO's interim guidelines for fuel cell ships propose a risk-based management principle, they lack detailed refueling operation procedures and emergency plans (Zhaka and Samuelsson, 2024). In addition, although some countries have issued training guidelines for crews of hydrogen-powered ships, there are still no mandatory requirements at the international level. Crew members generally lack standardized training in maintaining fuel-cell systems or handling hydrogen leakage.

Lack of Multi-Energy Synergy Control Standards: Ship propulsion systems must integrate multiple energy sources, including fuel cells, energy storage batteries, and renewable energy. However, the current standards have not yet been refined in terms of the regulations on key technologies such as energy scheduling algorithms and fault-redundancy mechanisms. This immature standards system increases the difficulty of system integration and limits improvements in the economic and reliability performance of hydrogen-powered vessels.

Weak Environmental Adaptability Standards: The impact of marine environmental conditions on the lifespan of hydrogen fuel cells (e.g., high salt mist corrosion and mechanical vibration) has not been quantified in evaluation standards. Current testing specifications are primarily based on automotive scenarios and do not account for the specific vibration spectra and salt mist cycling test requirements for vessels, which could result in a potential reduction in equipment service life compared to design expectations.

5.1.2 Technical challenges and limitations of marine fuel cells: durability, power density, and system integration

Existing fuel cell technology is primarily derived from hydrogen fuel cell systems used in the automotive sector. However, marine fuel cells face significant limitations due to the unique operational conditions of ships. The harsh maritime environment is compounded by constrained onboard space and shorter safety distances compared to land-based installations. Marine fuel cells must withstand high salt mist exposure, wave impacts, and continuous vibrations and oscillations (Wang et al., 2023). Additionally, vessels require significantly higher power than automobiles, necessitating larger-scale hydrogen storage and supply systems. These factors contribute to the technological immaturity of marine fuel cells, highlighting the need for further advancements in adaptation, durability, and large-scale integration to meet the stringent demands of maritime applications.

Technical Challenges of Marine Fuel Cell Durability: Marine fuel cell technology still faces multiple technical challenges in practical applications, particularly in terms of environmental adaptability and reliability, which have not yet met the requirements of marine propulsion systems (Wang et al., 2023; Xing et al., 2021). The durability of fuel cells is significantly lower than that of traditional marine diesel engines. Currently, the lifespan of the mainstream PEMFC generally does not exceed 10,000 hours, while marine diesel engines can last more than 20,000 hours. This discrepancy primarily arises from the multiple degradation mechanisms of fuel cells in the complex marine environment. Although breakthroughs have been made in the lifespan of PEM stacks, there is still a significant gap compared to the 50,000-hour target required for marine applications.

Insufficient Power Density: Current marine fuel cell systems generally have power outputs below 350 kW, whereas large vessels require propulsion power in the thousands of kilowatts. To meet these power demands, multiple stacks must be stacked to expand the system, but this leads to a significant increase in volume and weight, conflicting with the limited space available on ships (Mylonopoulos et al., 2024). For example, the 320 kW system in Norway requires the integration of multiple stacks, and Japan's 250 kW system uses a dual-stack configuration. Additionally, the technical paradox between high power density requirements and heat dissipation capacity arises, while increasing power density requires more compact electrode structures, this exacerbates local hotspots and mass transfer limitations.

System integration faces multiple technical challenges: The marine environment, characterized by high humidity, salt mist corrosion, and mechanical vibrations, imposes higher demands on fuel cell sealing, material corrosion resistance, and dynamic response capabilities. Existing systems are likely to experience uneven gas distribution and voltage fluctuations under variable load conditions, leading to efficiency losses and shortened lifespans (Xing et al., 2021; Mylonopoulos et al., 2024). Breakthroughs in material innovation, system optimization, and engineering verification are required for marine fuel cell technology to play a central role in the future decarbonization of shipping.

5.1.3 Challenges of high-pressure gaseous hydrogen storage in long-distance maritime applications

High-pressure hydrogen storage technology has advantages in terms of system maturity and adaptability, and it remains the mainstream choice for current ship hydrogen energy applications. However, its inherent limitations pose significant challenges to the large-scale hydrogen transition in deep-sea vessels. Specifically, the technology faces the following key challenges:

Conflict between hydrogen storage density and space utilization: The volumetric hydrogen density of high-pressure gaseous storage is limited by the physical characteristics of compression, with a density of approximately 25 g/L at 35 MPa, increasing to 40 g/L at 70 MPa. For large ocean-going vessels, the hydrogen required per voyage can amount to several hundred kilograms, necessitating multiple storage tanks. That results in a fuel system volume that may far exceed the total volume of the storage tanks themselves. This spatial demand sharply conflicts with the trend toward more compact vessel designs. The arrangement of multiple tanks must also account for weight distribution, safety distances, and dynamic load adaptability, further complicating the engineering design (Li et al., 2024c).

Hydrogen embrittlement and durability challenges with metal materials: Currently, hydrogen storage tanks primarily use aluminum alloys or steel liners, which are susceptible to hydrogen embrittlement when exposed to high-pressure hydrogen environments (Li et al., 2024c; Zheng et al., 2012). This can lead to material degradation and potential container failure (Habib et al., 2023). Additionally, frequent hydrogen charging and discharging cycles accelerate material fatigue, and ship vibrations, combined with salt mist corrosion, exacerbate these durability issues.

Hydrogen refueling efficiency and infrastructure deficiencies: The refueling time for current high-pressure gaseous hydrogen systems typically exceeds 2 hours, which is significantly longer than the land-based vehicle refueling. Ocean-going vessels, due to their routes, require frequent refueling. However, at present, only a few ports around the world have initiated pilot hydrogen refueling facilities. Moreover, the existing port facilities have deficiencies in hydrogen transport pressure, interface compatibility, emergency shutdown mechanisms and explosion-proof designs. Furthermore, ship refueling must synchronize with navigation and cargo handling operations, requiring higher standards for the real-time performance and redundancy of control systems.

5.2 The development prospects of hydrogen-powered vessels

5.2.1 Establishing a comprehensive and robust standardization framework for hydrogen-powered vessels

When it comes to hydrogen energy applications for maritime vessels, the establishment of comprehensive and scientifically rigorous technical standards and frameworks is of great importance. It is essential to transcend the applicability limitations inherent in automotive hydrogen energy standards and develop specialized regulations for marine fuel cell systems. These standards should address core technical parameters, such as battery consistency, thermal management design, and other critical aspects, to meet the requirements of maritime applications. Furthermore, for hydrogen storage technologies, it is crucial to establish detailed regulations for the installation of high-pressure cylinders and metal hydride storage systems (Davies et al., 2024; Sun et al., 2025). This will address the challenges associated with matching storage capacity to operational range and foster the revision of relevant guidelines by the IMO.

Subsequently, it is necessary to refine the technical specifications for hydrogen refueling systems (Jiang et al., 2025; Park et al., 2025) and set unified standards for parameters such as liquid hydrogen refueling rates and interface compatibility. A "risk-oriented + dynamic assessment" approach should be employed to manage hydrogen refueling infrastructure at ports, coupled with the development of more granular ship-to-shore operational protocols. Moreover, it is essential to enhance safety management standards across the entire lifecycle. This includes the creation of quantitative models for hydrogen leak dispersion (Li et al., 2025), the formulation of comprehensive emergency response manuals, and the incorporation of these protocols into crew training systems. A sophisticated risk assessment matrix should be developed to implement tiered safety certifications.

Meanwhile, the development of standards for multi-energy collaborative control technologies is necessary to overcome the constraints of single-energy systems. This includes the definition of collaborative control algorithms, fault tolerance mechanisms, and the establishment of a robust energy dispatch performance evaluation framework. Finally, an oceanic environmental adaptability assessment system must be established, accompanied by the formulation of environmental testing specifications and the integration of specialized testing requirements. The use of accelerated aging tests should be leveraged to establish correlation models, thereby enhancing the assessment of system durability and operational reliability.

5.2.2 Development of high-capacity, long-duration marine fuel cell technology

Future research needs to be conducted in the fields of material innovation, system optimization, environmental adaptability enhancement, and engineering validation. Regarding material innovation, it is recommended to develop corrosion-resistant catalysts and supports. For example, catalysts that can withstand chloride ion corrosion in high-salinity marine environments should be developed as alternatives to precious metals (Aziz et al., 2025). Additionally, optimizing the structure of carbon supports and exploring methods to suppress the Ostwald ripening effect could help extend the electrochemical active surface area. To enhance the mechanical stability of PEM, it is advisable to introduce binders or explore new solid-state electrolytes that can reduce the impact of mechanical stress.

In terms of system optimization, modular stacking and compact designs are valuable. Flexible interconnect technologies could enable dynamic configurations, while electrode structures can be optimized to improve the uniformity of gas distribution. Moreover, integrating energy storage and hybrid power systems, such as combining lithium-ion batteries, could create hybrid power architectures that reduce the frequency of fuel cell start-stop cycles and alleviate power stress on individual stacks. The development of high-efficiency heat dissipation and thermal management systems is also essential to prevent overheating.

Regarding environmental adaptability, the use of weather-resistant coatings and sealing technologies is beneficial. Hydrophobic coatings could be applied to key components, and elastic sealing materials could be used to enhance protection. Additionally, standardized testing and lifespan evaluation protocols should be developed to simulate marine operating conditions, creating lifespan prediction models that will guide design optimization. These advancements are crucial for improving the performance, durability, and operational efficiency of fuel cell-powered vessels in the maritime sector.

5.2.3 Innovative strategies of hydrogen storage and refueling systems for fuel cell vessels

It is essential to explore and implement a range of innovative frameworks to address the critical challenges associated with hydrogen storage and refueling. To overcome limitations in hydrogen storage density, a multi-technical approach is recommended. Liquid hydrogen storage tank technology should focus on optimizing multi-layer insulation structures and incorporating advanced vacuum system design techniques to effectively control thermal losses and improve loading efficiency (Davies et al., 2024). Additionally, liquid ammonia, as an intermediate hydrogen carrier, offers high hydrogen storage density and a relatively mild liquefaction temperature (Yin et al., 2024), making it a viable option for short- to medium-range voyages. Concurrently, the engineering application of 70 MPa Type IV plastic liner hydrogen storage tanks should be explored to develop lightweight and efficient hydrogen storage systems.

To enhance material durability, emphasis should be placed on optimizing adaptability to hydrogen environments. Specifically, the development of novel hydrogen-resistant alloys incorporating nanoparticle reinforcement and gradient coating technologies can help reduce hydrogen embrittlement sensitivity (Laadel et al., 2022). Additionally, dynamic load compensation designs should be implemented to mitigate vibrational deformations experienced during vessel operations. Accelerating lifespan evaluation systems is also crucial, as simulating composite environments can shorten the in-service validation period and improve reliability.

Regarding innovations in hydrogen refueling systems, the focus should be on ship-to-shore collaboration and smart technologies. The development of adaptive refueling arms, incorporating visual positioning systems and flexible joints, would enable high-precision compensation for berth misalignment (Wang et al., 2024a). Additionally, a hydrogen-electric collaborative control platform should be established to facilitate dynamic fuel cell power adjustments and seamless transitions to emergency power supplies. Furthermore, the IMO should continuously revise and refine the guidelines for ship hydrogen refueling systems and promote the development of standardized refueling infrastructure to enhance safety and efficiency during the refueling process.

6 Conclusion

The global shipping industry is undergoing a transformative shift toward decarbonization, with hydrogen-powered vessels emerging as a key technological solution to meet international emission reduction targets. As a zero-emission fuel, hydrogen plays a crucial role in aligning the shipping sector with the IMO's greenhouse gas reduction strategy, particularly its goal of reducing emissions by 50% by 2050. Regulatory frameworks such as the IMO's GHG reduction strategy, the MARPOL Convention, and regional policies, including the EU's Emissions Trading System, provide essential guidance and incentives for adopting hydrogen technologies. These regulations drive the integration of hydrogen fuel cells, the optimization of ship designs for energy efficiency, and the development of hydrogen infrastructure, fostering a low-carbon transition in maritime transport. Ongoing regulatory advancements from the IMO and classification societies further enhance safety, technical feasibility, and operational reliability. Pioneering case studies, such as the "Viking Lady" and "Energy Observer" demonstrate the viability and potential of hydrogen as a clean energy source for maritime propulsion.

However, challenges related to hydrogen storage, fuel cell integration, and operational safety persist, necessitating continuous innovation in vessel design and strict adherence to regulatory standards. Hydrogen storage technology is a critical factor in the development and commercialization of hydrogen-powered vessels, directly influencing their range and safety. While high-pressure gaseous hydrogen storage remains the most mature solution, it faces significant spatial and safety challenges due to its low volumetric energy density. Cryogenic liquid hydrogen storage, despite offering higher energy density, is still in the exploratory phase, facing challenges in maintaining ultra-low temperatures and system integration. LOHC technology and metal hydride storage present promising alternatives, but both are hindered by high dehydrogenation energy consumption and integration complexities. Future advancements in these storage technologies —focusing on efficiency, safety, and scalability—are essential for enabling the widespread adoption of hydrogen-powered vessels and supporting the maritime sector's transition to sustainable, low-carbon operations. Meanwhile, the integration of marine fuel cell systems is hindered by issues such as limited durability, power density, and environmental adaptability, necessitating substantial technological advancements. In addition, hydrogen-powered ships still face numerous challenges in terms of safety standards and technical regulations. These challenges all impede the large-scale application and commercial promotion of hydrogen-powered ships.

To address these challenges, first of all, a comprehensive, scientifically-rigorous technical standard and safety framework applicable to hydrogen-powered ships should be established, the technical specifications of the hydrogen refueling system should be detailed, an evaluation system for marine environmental adaptability should be established, and the safety management standards throughout the entire life cycle should be improved. Secondly, it is also necessary to innovate in hydrogen storage and refueling systems and develop fuel cells with high capacity, long service life and suitability for the marine environment. These advancements are crucial for enhancing the performance, durability and operational efficiency of hydrogen-powered ships. With the continuous improvement of relevant policies and regulations and the continuous maturity of hydrogen technologies, hydrogen-powered ships will play an increasingly important role in global shipping decarbonization and ultimately contribute to international climate goals and the progress of sustainable maritime practices.

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