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Review article

A review on the research progress and application of compressed hydrogen in the marine hydrogen fuel cell power system

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ABSTRACT

The urgency to mitigate greenhouse gas emissions from maritime vessels has intensified due to the increasingly stringent directives set forth by the International Maritime Organization (IMO). These directives specifically address energy efficiency enhancements and emissions reduction within the shipping industry. In this context, hydrogen is the much sought after fuel for all the global economies and its applications, for transportation and propulsion in particular, is crucial for cutting down carbon emissions. Nevertheless, the realization of hydrogen-powered vessels is confronted by substantial technical hurdles that necessitate thorough examination. This study undertakes a comprehensive analysis encompassing diverse facets, including distinct variations of hydrogen fuel cells, hydrogen internal combustion engines, safety protocols associated with energy storage, as well as the array of policies and commercialization endeavors undertaken globally for the advancement of hydrogen-propelled ships. By amalgamating insights from these multifaceted dimensions, this paper adeptly encapsulates the myriad challenges intrinsic to the evolution of hydrogen-fueled maritime vessels, while concurrently casting a forward-looking gaze on their prospective trajectory.

1. Introduction

In the current era of globalization, maritime transport has emerged as the linchpin for an overwhelming majority of global freight movements, accounting for a staggering 90 % of all such activities. This pivotal role is divided into two principal categories: military vessels and civilian ships, the latter constituting the foundational stratum of the shipping domain. Within the realm of civilian ships, a bifurcation emerges based on their intended functions, delineating transport ships and marine engineering ships as the primary constituents. Significantly, transport ships occupy a preeminent position within this categorization. Specifically, the triumvirate of dry bulk carriers, oil tankers, and container ships, collectively denoted as transport vessels, commands an impressive share, eclipsing 90 %

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of the entire deadweight tonnage—a fact that designates them as the “three principal ship types" globally. In contrast, higher-value offshore engineering vessels and liquefied gas carriers manifest intricate construction methodologies and materials, underscoring their elevated status [1,2]. Compounding these trends, a poll conducted by the esteemed Clarkson Foresight Industrial Research Center reveals that, as of 2020, shipping operations bear the responsibility for a significant 2.4 % of global carbon dioxide emissions and a noteworthy 15 % of carbon-nitrogen oxide emissions. Recognizing the pressing need for transformative action, the International Maritime Organization (IMO) has charted a roadmap for 2050 [3]. This roadmap outlines a compelling vision, aiming to curtail worldwide ship-related CO_2 and greenhouse gas emissions to under 50 % of the 2008 benchmarks. This ambitious objective not only aligns with the aspiration of global carbon neutrality but also represents a pivotal step toward mitigating the detrimental environmental impact attributed to the scourge of ship emissions pollution [4,5].

In light of the International Maritime Organization’s (IMO) comprehensive directives encompassing the 2020 carbon peak, sulfur limit, and carbon neutrality imperatives, the maritime sector finds itself at the precipice of a paradigm-shifting green transformation. This impetus has spurred the ascension of the investigation into clean, efficient, and sustainable alternative energy propulsion technologies, which holds pivotal significance in ushering in an era of environmentally conscious maritime operations. In juxtaposition to the automobile industry, the maritime domain is uniquely characterized by usage contexts that demand intricate technology synchronization. This complexity emanates from the diverse operational demands posed by ships, necessitating precise alignment between technology and application. Within this context, the integration of lithium-powered systems in long-haul, heavy-duty, extended-duration scenarios faces formidable challenges. The applicability of lithium-based systems in the maritime milieu is considerably restrained due to their limited transposability. In this unfolding scenario, the international community’s anticipation has progressively converged upon the trajectory of hydrogen and its derivatives, such as ammonia, as instrumental catalysts in the maritime energy landscape. The allure of hydrogen-driven energy stems from its inherent attributes—readily accessible, pristine, devoid of carbon emissions, high-energy density, adaptability, efficiency, sustainability, low acoustic and vibrational profiles—rendering it an ideal partner for synergistic amalgamation with other renewable energy sources. Consequently, myriad nations and eminent shipping conglomerates have positioned hydrogen energy at the forefront of their developmental agendas, discerning its potential as a potent antidote to fossil fuels. This visionary perspective extends to encompass large-scale deep decarbonization not only of the transportation sector but also various other domains, thereby propelling it into the pivotal role of a “double carbon" strategy. The strategic fusion of hydrogen energy and fuel cell technology stands as an instrumental axis within the global discourse of energy transition and power paradigm shift. This strategic maneuver not only addresses the specter of worldwide energy dearth but also the escalating menace of environmental contamination. The manifold virtues of hydrogen fuel cells—efficiency, ecological benignity, serenity, and reliability—have garnered the attention of the global stage and major maritime entities alike, thus underscoring their significance in steering the course of maritime evolution.

In recent times, significant strides have been taken in the seamless integration of hydrogen into power systems, encompassing every stage from production and storage to re-electrification and the paramount concern of safety. A multitude of researchers have embarked upon endeavors aimed at delineating the current panorama of hydrogen system integration, employing distinctive methodologies to capture its multifaceted evolution. Elaborated expositions on the contemporary advancements in this arena have been expounded elsewhere [6], offering a comprehensive overview of the ongoing progress. Collectively, the research community arrives at a consensus that harnessing renewable energy sources for hydrogen production bears immense promise for fostering the sustainability of global progress [7]. As articulated by Chi et al. the adoption of renewable electricity engenders enhanced synergy between electricity and hydrogen, thereby broadening the spectrum of potential applications for the latter [8]. This verity has incited a multitude of explorations into various facets of renewable hydrogen production technologies, kindling widespread curiosity [9]. An innovative avenue explored within this domain involves the utilization of photocatalysis to derive hydrogen from renewable sources, as expounded upon in Refs. [10,11]. This ingenious approach capitalizes on solar energy to effectuate water splitting, thereby engendering hydrogen production. Concomitantly, endeavors aimed at curtailing energy consumption during hydrogen manufacturing have garnered attention, epitomized by the in-depth investigations by Wang et al. [12], which have gravitated towards intensification technologies at the component level. The progression also extends to pioneering power-to-gas initiatives at the systemic echelon, a realm that has been meticulously examined and scrutinized [13,14]. A granular exploration of power-to-gas applications has encompassed cost considerations and capacity evaluations of electrolysis and methanation [15], alongside probing the reverberations of hydrogen injection on gas infrastructure and quality [16]. Considering that the majority of power-to-gas installations are strategically sited proximate to remote renewable energy sources, the conundrum of storing produced hydrogen before its injection into the gas distribution framework has precipitated a surge in studies aimed at augmenting storage capacities [17]. Despite this, the techno-economic viability of prevailing hydrogen storage systems has been scrutinized by Abe et al. revealing a gap that necessitates further research, especially pertaining to solid hydrogen storage [18]. Meanwhile, the assurance of the efficacy and security of existing methodologies for hydrogen storage and distribution has garnered scholarly attention [19]. Underscoring the exploratory nature of this field, Von Colbe et al. [20] have conducted a comprehensive analysis, elucidating the deployment of hydrides for hydrogen storage in both stationary and mobile applications. This exhaustive inquiry traverses the multifaceted landscape, offering insights into the feasibility and potential of this storage methodology.

The structure of this paper is meticulously delineated as follows: The second section delves into a comprehensive overview of the contemporary landscape of hydrogen fuel cell development. Subsequently, the third segment is dedicated to an intricate exploration of the ongoing advancements in hydrogen-propelled ship development, further elucidating the nuances of ship hydrogen storage technology. In this context, the section also undertakes an in-depth examination of the policies formulated by prominent nations to propel ship hydrogen development, accompanied by a comprehensive analysis of the commercialization trajectory. Proceeding, the fourth section pivots to an astute dissection of the current array of predicaments and challenges besetting the realm of hydrogen-powered ship evolution. This evaluative stance seeks to encapsulate the intricacies intrinsic to the developmental process. Turning the spotlight to recent strides, the fifth and sixth sections serve as a conduit for conveying a cluster of pioneering advancements in the realm of ship hydrogen technology. These segments are designed to encapsulate a succinct representation of the latest breakthroughs and innovations within this domain.

2. The current situation of hydrogen fuel cell development

In the broader landscape of the energy system, hydrogen emerges as a distinctive entity, simultaneously embodying parallels and contrasts with other constituents. Analogous to electricity, hydrogen is a potent fuel, amenable to synthesis via renewable energy resources, and capable of recharging batteries, effectively represented by its role within a fuel cell. Akin to fossil fuels, hydrogen is endowed with combustive attributes, rendering it explosive and engendering heat upon combustion. However, these resemblances are juxtaposed against its remarkable divergences. Indeed, akin to other fuels, hydrogen can be dissociated from hydrocarbons, and it boasts the potential for prolonged storage periods. It can be seamlessly transported via pipelines, a facet that aligns with the conventional paradigms of energy conveyance. Notably, hydrogen can transition from a gaseous to a liquid state, facilitating its transportation and utilization. This versatility extends to its malleability into diverse derivatives, echoing its potential to assume varied forms and functions [21]. In this fashion, hydrogen presents itself as an amalgamation of attributes that mirror and diverge from its energy counterparts, encapsulating a multifaceted potential within the energy mosaic.

1. Hydrogen, although being the most abundant element on Earth, predominantly exists within compounds, primarily as water when combined with oxygen, and also in conjunction with hydrocarbons. This intrinsic composition underscores its dual identity as a renewable energy source with low carbon content, while simultaneously outlining the challenges in its cost-intensive generation. The attainment of hydrogen in its pure form demands liberation from its oxygen bonds, a process that necessitates careful extraction from hydrocarbons. This transformation is pivotal in rendering hydrogen a viable energy carrier and an emission-free fuel. Despite its elemental simplicity, the production of pristine hydrogen is riddled with complexities. The procedure is not only economically demanding but also generates carbon emissions, exemplifying its energy-intensive nature that impinges on substantial energy consumption. The impetus driving the wide-scale adoption of hydrogen predominantly hinges on its potential to drive the decarbonization of the energy landscape, particularly within sectors that present formidable challenges in emission reduction, such as the shipping industry. Consequently, the paramount objective crystallizes into a dual-fold endeavor: to engineer hydrogen production and transportation pathways that exhibit minimal to negligible emissions, while also leveraging the byproducts of water electrolysis, including waste heat and oxygen. This multifaceted aspiration is fundamentally rooted in the urgency to devise a holistic ecosystem that not only facilitates hydrogen's green utilization but also harnesses its potential to drive a paradigm shift in emissions reduction, thereby steering the energy domain towards a sustainable trajectory.
2. When juxtaposed against more familiar alternatives like natural gas or gasoline vapor, hydrogen exhibits flammability characteristics that are distinct, albeit with nuanced variances from natural gas. Hydrogen, while inherently flammable, unveils distinctive ignition dynamics. It ignites with remarkable ease, necessitating minimal energy input, all the while showcasing an expansive range of flammability. This broad spectrum accentuates hydrogen's versatility in combustion scenarios. The differentiation in hydrogen's behavior is palpable when it comes to dispersal, a facet intricately tied to its atomic structure characterized by minuscule atoms. This distinct composition imparts unique dispersion patterns, setting it apart from other gases. Moreover, hydrogen's intrinsic traits—being colorless, tasteless, and odorless—pose certain detection challenges. Addressing these limitations necessitates specialized sensors or odorants to facilitate its identification. Furthermore, additives are required to confer a discernible visual flame color when hydrogen undergoes combustion. This essential modification addresses the innate lack of visual cues, ensuring the perceptibility of hydrogen combustion events.
3. Despite its low energy density, hydrogen bears the distinction of being exceptionally lightweight, owing to its status as the lightest elemental constituent. This attribute engenders a notable advantage in scenarios where weight is a critical factor, such as in the domain of heavy road hauling. The juxtaposition of its lightweight quality and relatively high energy density, concerning its weight, renders hydrogen a favorable option within weight-sensitive applications. Nonetheless, it's imperative to contextualize this advantage within the broader framework of energy density, as hydrogen's energy density remains significantly lower than that of other conventional fuels. This divergence holds crucial significance and underscores the necessity for comprehensive considerations beyond the mere acknowledgment of this fact. This inherent characteristic accentuates the complexities involved in both storing and transporting hydrogen, due to the fundamental trade-off between its energy content and volume. In contexts where direct or conventional electrification is unfeasible, such as transportation and aviation, hydrogen's viability faces certain limitations, particularly in its gaseous state. To surmount this challenge, avenues to enhance the practicality of hydrogen manifest. One promising approach involves condensing hydrogen into a liquid form, thereby ameliorating its energy density and facilitating handling. Alternatively, hydrogen can be channeled into derivatives like ammonia, methanol, or synthetic fuels, diversifying its applicability and circumventing the constraints posed by its inherent energy density. This nuanced understanding illuminates the multifaceted strategies deployed to harness the potential of hydrogen across various domains, accentuating its adaptability and potential for transformative applications.
4. Compressed hydrogen emerges as a pragmatic approach for the cost-effective transportation of substantial hydrogen quantities across extended distances. This method, while economical, necessitates the establishment of an intricate network of transportation pipelines, accompanied by the inherent challenges associated with this mode of conveyance. This encompasses an array of technical complexities, underscoring the multifaceted nature of hydrogen logistics via compression. Another avenue explored in

hydrogen transportation is liquid hydrogen and its attendant derivatives. This approach, while capable of surmounting certain limitations, introduces inefficiencies and notable expenses due to the conversion processes involved. The conversion of hydrogen to liquid form or its derivatives necessitates energy input, thereby attenuating the overall energy efficiency. In contrast to alternatives like natural gas or biomethane, hydrogen may demand varying operating pressures or velocities, which can potentially exert deleterious effects on material integrity. The interplay between hydrogen's distinct operational parameters and the material constraints inherent to transportation systems necessitates meticulous engineering and design considerations. In essence, the choice of hydrogen transportation methodology involves a judicious evaluation of factors such as economics, technical feasibility, efficiency, and material compatibility. This discerning assessment is indispensable in devising a robust infrastructure that can effectively accommodate the intricacies of hydrogen transport, thereby unlocking its potential to contribute to a sustainable energy landscape.

The landscape of hydrogen's potential within the context of the energy transition is vast, yet it is not devoid of formidable challenges. The energy ecosystem intertwined with hydrogen encompasses multiple facets, from its generation to the separation or extraction of water, inevitably leading to the crux—the energy content of the produced hydrogen. Crucially, this energy content is limited by the energy content of the input fuel and further augmented by the energy required for hydrogen synthesis. This paradigm results in substantial losses attributed to inefficiencies ingrained in both the production and conversion stages. The exigencies of hydrogen storage and transportation compound these challenges, culminating in energy expenditures that often surpass those associated with conventional fuels. To rationalize and mitigate the energy losses incurred throughout hydrogen's lifecycle—spanning its manufacture, transit, and utilization—it becomes imperative for the intrinsic value of pure hydrogen, be it to consumers or society as a whole, to be sufficiently profound. In essence, the equation hinges on a delicate balance between energy inputs, efficiency optimization, and the tangible value proposition that hydrogen extends. This intricate equilibrium is central to engendering the viability of hydrogen as a formidable player within the energy transition landscape, one that effectively outweighs the inherent energy trade-offs it engenders.

Henceforth, hydrogen energy finds its primary utilization within maritime vessels, predominantly through two distinct power unit paradigms. The first avenue encompasses novel power units, specifically fuel cells, which are being harnessed to galvanize a new era of propulsion. Concurrently, the second pathway involves the integration of traditional heat engines, manifesting in two manifestations: one is the direct application of internal combustion engines fueled by pure hydrogen, while the other entails the adoption of internal combustion engines fueled by ammonia or methanol, rendering it an indirect application. In essence, the maritime domain stands as a pioneering frontier in deploying hydrogen energy, enlisting an array of innovative propulsion mechanisms that span the gamut from futuristic fuel cells to adeptly modified conventional engines. This multifaceted approach exemplifies the maritime industry's relentless commitment to revolutionize its energy landscape, effectively harnessing the potential of hydrogen to transcend the boundaries of traditional power paradigms.

2.1. Hydrogen internal combustion engine

In the realm of maritime propulsion, employing a hydrogen internal combustion engine offers a streamlined path to industrial implementation. This approach garners favor due to its minimal impact on the ship's hull structure, remarkable durability, lower hydrogen purity requirements, and a mature manufacturing ecosystem marked by cost-effective production. However, it's pertinent to recognize that the hydrogen internal combustion engine, while offering advantages, is not ideally suited to serve as the sole propulsion source for a vessel. Its characteristics, characterized by soft output and gradual transient response, render it more suitable for deployment as a ship's power station generator or within hybrid propulsion systems, synergizing with energy storage batteries. Novel methodologies have been proposed to mitigate the emissions of hydrogen internal combustion engines, with the concept of unburned hydrogen introduced by Liu et al. [22]. This strategy remarkably reduces NOx emissions from a hydrogen internal combustion engine equipped with a TWC (Three-Way Catalyst), thus illustrating its potential to enhance emission profiles. Research by Boretti underscores the prowess of hydrogen internal combustion engines when integrated with hybrid powertrains. This configuration unveils impressive fuel conversion efficiencies, culminating in peak values surpassing 50 %, along with average efficiencies exceeding 35 % across driving cycles [23]. The utilization of hydrogen within engine cylinders, however, isn't bereft of challenges. Hydrogen's elevated auto-ignition temperature necessitates meticulous timing and combustion management within the cylinder [24,25]. Spark-ignition engines can exclusively operate on hydrogen as a solitary fuel, whereas compression engines mandate a dual-fuel approach wherein hydrogen is co-utilized with a hydrocarbon pilot fuel [26]. Distinct hydrogen storage techniques intersect with varied fuels. Fuels like FTS-fuels, *S*-LNG, and methanol can be directly employed in combustion engines. Conversely, ammonia necessitates a dual-fuel configuration with a pilot fuel due to its high auto-ignition temperature and constrained flammability range. Innovative research from the University of Pisa [27,28] delves into the possibility of using an integrated reactor to fractionate ammonia into nitrogen and hydrogen, the latter then serving as a pilot fuel for ammonia combustion. Intriguingly, formic acid emerges as a prospect within the exhaust gas of methanol engines. However, its oxidation renders it unsuitable for combustion engines unless accompanied by pure hydrogen in the combustion mixture, as evidenced by research conducted by Sarathy et al. [29] Leveraging Liquid Organic Hydrogen Carriers (LOHCs) within combustion engines offers a notable advantage by enhancing tolerance to fuel impurities. Nonetheless, the trade-off surfaces in the form of reduced power efficiency compared to fuel cells, compelling a balance between releasing hydrogen from the carrier and expending energy on purification. In summation, the deployment of hydrogen internal combustion engines within maritime applications represents a dynamic interplay between advantages, challenges, and potential solutions, necessitating a judicious evaluation to realize their practical and environmental merits.

2.2. Hydrogen fuel cell

Marine internal combustion engines typically have a thermal efficiency of approximately 40 %. In contrast, hydrogen fuel cells are emerging as a highly efficient alternative, with an efficiency range that extends from 50 % to 80 % [30]. Furthermore, a notable advantage of hydrogen fuel cells lies in their minimal vibration and noise levels, attributing to their enhanced operational serenity. Within the realm of fuel cell technology, several variants have garnered prominence due to their applicability. These encompass alkaline fuel cells (AFC), phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), proton exchange membrane fuel cells (PEMFC), and direct methanol cells (DMFC). Among these, proton exchange membrane fuel cells (PEMFC) occupy a significant position and can be subdivided into low-temperature PEMFC (referred to as PEMFC) and high-temperature PEMFC (abbreviated as HT-PEMFC). The salient components and essential technical specifications of fuel cells are presented in Table 1, succinctly encapsulating the pivotal aspects that define their operational attributes. This diverse spectrum of fuel cell types underscores the breadth of options available, each offering distinct advantages and nuances that cater to specific applications within the maritime domain.

Among various fuel cell technologies, alkaline fuel cells have established themselves as a well-established option, although they are being progressively supplanted by newer and more advanced alternatives. In Japan, a solitary project centered around methanol fuel cells has been validated, but its limited power density undermines its viability. These methanol fuel cells initially found application in small portable electronic devices, such as notebook computers and mobile phones [33]. Proton exchange membrane fuel cells (PEMFC) have emerged as a frontrunner, reaping an array of advantages including high power density, operation at low temperatures, and commendable dynamic responsiveness. However, the intricate intricacies of PEM fuel cell design and the specificities of operating conditions necessitate a tailored approach to measurement and control methodologies. To optimize cell performance, Fuel Cell Models (FCMs) prove instrumental in deciphering optimal design and operational parameters. An operationally-relevant model devised by Hung et al. delved into the influence of operational parameters, such as temperature, humidification temperature, pressure, and gas stoichiometric ratios, on cell performance. By meticulously varying these parameters and analyzing the model's predictive capability, insightful results were garnered [34]. Yuan et al. [35] underscored the correlation between enhanced PEM fuel cell performance and elevated operating pressure and temperature. Their findings illustrated that PEM fuel cells exhibit superior performance under heightened pressure conditions. Consequently, proton exchange membrane fuel cells have captured substantial attention within the automotive and marine fuel cell domains. However, proton exchange membrane cells typically operate within an optimal output power range below 300 KW [36]. For applications demanding higher power outputs, such as in ocean-going vessels, solid oxide fuel cells and molten carbonate fuel cells take precedence due to their elevated operating temperatures, typically ranging from 600 to 700 °C [37]. This heightened thermal regime bestows the capability to generate high-quality heat, catering not only to the crew's hot water requirements during extended voyages but also synergizing with a gas turbine to generate electricity. This collaborative approach culminates in combined thermal efficiencies that may exceed 60 % [38], thereby extending the operational duration of ocean-going vessels and concurrently curtailing fuel consumption. Fig. 1 shows the hydrogen production and applications.

Fuel cells can be classified into two primary categories based on the oxidant they use: hydrogen-air fuel cells and hydrogen-oxygen fuel cells. The choice of oxidant holds significant implications for specific applications. Notably, submarines and underwater autonomous vehicles predominantly rely on hydrogen-oxygen fuel cells. Conversely, when employing hydrogen-air fuel cells in ships, a critical consideration arises—the design of a specialized air filter. This design element is indispensable to shield the fuel cell from the corrosive impact of sea air's heightened salt content. The integration of hydrogen-air fuel cells within marine vessels necessitates meticulous engineering to ensure the longevity of the fuel cell under maritime conditions. Despite hydrogen possessing the highest mass-energy density among fuels, its bulk energy density remains remarkably low. Comparatively, diesel, while having a relatively modest mass-energy density, outperforms hydrogen significantly in terms of volumetric energy density. To illustrate, the volumetric energy density of hydrogen compressed to 35 MPa is merely around 10 % of that exhibited by diesel [40]. Consequently, the transition from a diesel engine to a fuel cell for power supply warrants due consideration, as the volumetric space necessitated for high-pressure hydrogen storage exceeds the volume required for diesel fuel tanks. Embracing hydrogen as a fuel source for fuel cells imposes

Table 1
Fuel cell main components and key technical parameters [31,32].

Type		AFC	PEMFC	HT-PEMFC	PAFC	DMFC	MCFC	SOFC
Electrodes	Anode	Pt/Ag	Pt/C	Pt/C	Pt/C	Pt/C	Li/NiO	Sr/LaMnO$_2$
	Cathode	Pt/Ni	Pt/C	Pt/C	Pt/C	Pt–Ru/C	Ni/Al,Ni/Cr	Ni/YSZ
Electrolytes		Potassium hydroxide	Aqueous polymer films	Inorganic acid-based polymer films	Phosphoric acid	Aqueous polymer films	Fused carbonates	Porous ceramic materials
Fuels		H_2	H_2	H_2	H_2, LNG, Methanol	Methanol	H_2, methanol, hydrocarbons	H_2, methanol, hydrocarbons
Operating temperature/°C		60~200	65~85	160~220	140~200	75~120	650~700	500~1000
Power Capacity/KW		≤ 500	≤ 120		100~400	≤ 5	120~10,000	≤ 10^7
Electrical efficiency/%		50~60	50~60	50~60	40~55	20~30	50~55	50~60
Price		Low	Low	Medium	Medium	Medium	High	High
Lifespan		Medium	Medium	Medium	Good	Medium	Good	Medium
Size		Small	Small	Small	Large	Small	Large	Medium

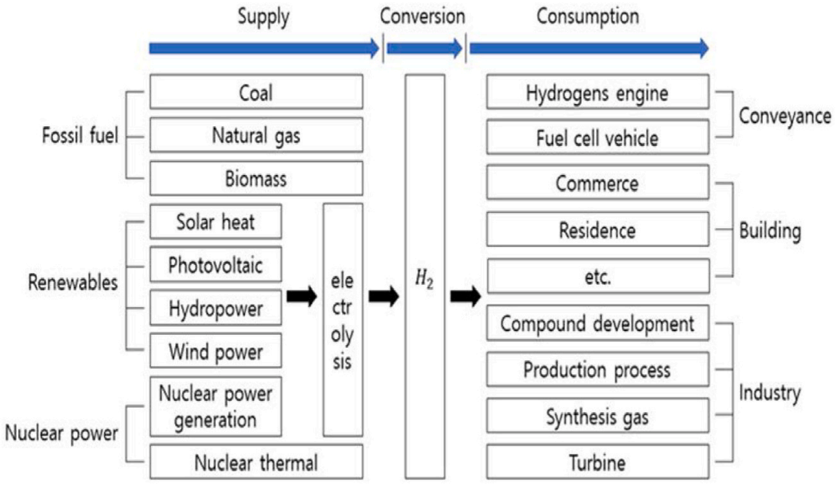

Fig. 1. Hydrogen production and applications [39].

additional demands on the ship's fuel tank design, particularly concerning size and security. Relationship between hydrogen production and storage and end-use applications as shown in Fig. 2. Hydrogen's characteristics, including lower density, heightened susceptibility to leakage, flammability, and explosive nature, mandate a robust infrastructure to ensure safety and operational integrity. In summation, while hydrogen presents unparalleled potential as a fuel source for fuel cells, its implementation within maritime applications necessitates a comprehensive understanding of its attributes, intricacies, and the requisite engineering adaptations to ensure both efficiency and safety. Table 2 shows that characteristics of water-electrolytic hydrogen production.

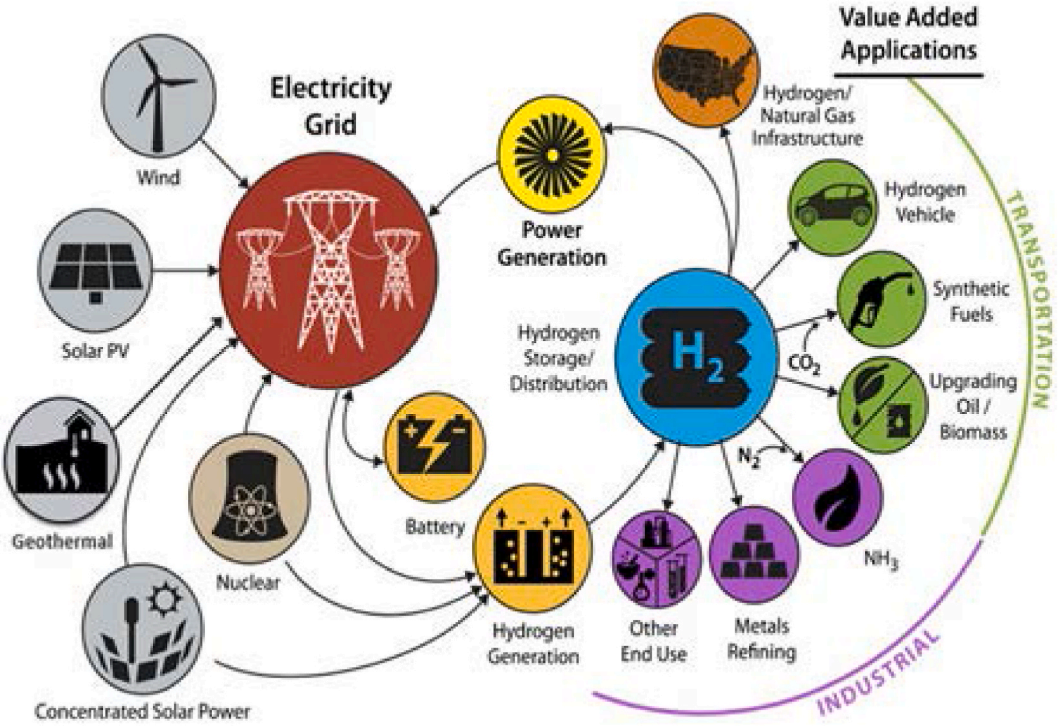

Fig. 2. Relationship between hydrogen production and storage and end-use applications [41].

Table 2

Technical characteristics of various hydrogen production electrolyzed water [42,43].

Typology	Working temperature/°C	Pressures/ MPa	Current density/ (A·cm^{-2})	Unit energy consumption/(kWh/ Nm^3)	Electrolytic efficiency/%	Purity of hydrogen/%	Responsiveness	Adjustment range/%	Application Scenarios in Power Systems
AWE	70~90	1~3	$<$ 0.8	4.5–5.5	56~80	≥99.8	tens of seconds	15~120	Deep and efficient wind and solar energy consumption/grid flexible interaction
PEM	50~80	2~5	0.1–2.2	3.4–4.4	76~85	≥99.99	order of seconds	0~150	Fast and flexible regulation of the power grid
AEM	≤60	0.1–3	0.2–1	4~4.8	60~78	≥99.99	_	_	_
SOE	500~1000	1~2	1~2	2.23–2.27	90~100	≥99.9	minute	0~120	Nuclear/Industrial Waste Heat to Hydrogen

3. Status of hydrogen ship development

3.1. High pressure hydrogen storage and transportation standards and safety

The progression towards green shipbuilding and sustainable maritime operations has evolved into a pivotal trajectory, embodying the essence of future-oriented development within the shipping industry. Within this transformative landscape, the hydrogen fuel cell system emerges as an unrivaled propulsion solution for ushering in the era of green ships. Its distinctive attributes, including remarkable energy conversion efficiency, minimal vibration and noise output, emission-free operation, and absence of pollution, stand in stark contrast to conventional ship power systems like steam turbines and diesel engines. This paradigm shift towards hydrogen fuel cell systems aligns seamlessly with the imperatives of green shipping, enabling a tangible leap towards sustainable marine operations. The viability and efficacy of hydrogen fuel cell ships are intrinsically linked to various factors, encompassing speed, range, safety, and economic considerations. These facets are intricately tied to the characteristics of hydrogen storage devices, particularly their storage density, replenishment capabilities, system intricacy, and cost. The successful integration of hydrogen fuel cell systems within maritime vessels hinges on the efficient and high-safety storage and transportation of hydrogen. This pivotal aspect stands as the linchpin, dictating the practical applicability of hydrogen energy within the maritime domain. In essence, the trajectory towards greener shipping necessitates the confluence of technological innovation, strategic investments, and a steadfast commitment to minimizing environmental impact. The hydrogen fuel cell system emerges as a potent catalyst within this journey, encapsulating the ethos of sustainability, efficiency, and a vision of a cleaner, more responsible maritime industry.

Presently, high-pressure gaseous hydrogen storage technology has achieved a commendable level of industrial maturity. However, its application scope remains constrained due to the inherent limitations of hydrogen's low storage density. As a consequence, this technology primarily finds suitability for specific marine vessels, particularly excursion ships and ferry boats characterized by low power requirements and short operating ranges. In essence, the utilization of high-pressure gaseous hydrogen storage predominantly aligns with maritime applications that demand modest power output and constrained travel distances. Conversely, vessels that necessitate substantial power and the ability to traverse longer distances necessitate an alternative approach, often manifested in the form of high-density hydrogen storage methodologies. Prominent examples include liquid hydrogen storage and hydrogen storage systems that are derived from fuel reformulation, particularly enriched with biomass-derived components. Liquid hydrogen storage presents itself as a notable contender within this landscape due to its simplified standardization and administration procedures. In essence, the choice of hydrogen storage technology for maritime applications is intricately tied to the specific operational parameters of each vessel, encompassing power requirements, travel range, and the overarching need for efficiency, safety, and environmental responsibility. This discerning selection process is integral in sculpting the energy landscape of ships, striking a delicate equilibrium between technological feasibility and operational practicality.

In addition to direct hydrogen storage, an alternative approach for harnessing hydrogen energy in ships involves using liquid ammonia and methanol, derived from low-carbon hydrogen synthesis. Methanol, for instance, can leverage fuel reforming technology to create a hydrogen and carbon monoxide (CO) gas mixture, which can then be directly introduced into a high-temperature fuel cell for reaction. This strategy effectively addresses the challenge of hydrogen's poor volumetric energy density. While a significant proportion of marine vessels opt for high-pressure hydrogen storage due to its well-established maturity, rapid charging and discharging capabilities, simplicity, high hydrogen storage density per unit of weight, and cost-effectiveness, there are both merits and limitations to consider. However, for smaller and medium-sized ships with energy storage capacities of a few MWh or less, high-pressure hydrogen storage comes with disadvantages like low volumetric hydrogen storage density, potential safety risks related to leakage, and inefficiencies in replenishment processes. Liquid hydrogen storage, on the other hand, boasts benefits including high hydrogen storage density in terms of weight and volume, as well as rapid replenishment. However, it also comes with its own set of challenges, such as energy-intensive hydrogen liquefaction processes, high daily evaporation rates, demanding safety and control requirements, and limitations in long-term closed hydrogen storage, utilization, and transportation. The journey of liquefying hydrogen dates back to Sir James Dewar's successful attempt in 1898 [44]. Over the years, various cooling pathways, including helium refrigeration systems, the Linde-Hampson [45], Claude [46], pre-cooled Claude cycle [46], and Claude cycle methods [47], have been developed for liquid hydrogen production [48]. While different pathways exist, helium-cooled liquid hydrogen generation stands out as one of the most effective methods. Nevertheless, challenges remain. Today's studies on the usage and storage of liquid hydrogen are still heavily influenced by the aerospace sector [49–53]. The low temperatures required for fueling and the consequent evaporation of liquid hydrogen present significant hurdles. Specially designed insulating materials are necessary to minimize heat flow into the tank [54]. According to NASA, 45 % of the liquid hydrogen that was purchased for the space shuttle launch was lost throughout the supply chain, even before it got to the shuttle's fuel tank. 12.6 % of this was lost during the transfer from the trucks transporting the liquid hydrogen to the big storage tank, and 20.6 % of the liquid hydrogen was lost during the transfer from the on-site storage tank to the fuel tank for the space shuttle [55]. As the liquefaction of hydrogen requires a lot of energy, it is important to minimize the loss of liquid hydrogen in order to maintain the highest possible level of energy efficiency throughout the entire process. Despite the fact that there are uses for liquid hydrogen loading, including with its current HySTRA (HySTRA is the abbreviation of Japan CO_2-free Hydrogen Energy Supply Chain Technology Research Association. The organization was founded by Iwatani, Kawasaki Heavy Industries, Shell Japan and J-POWER) initiative, Kawasaki hopes to change this [56]. Notably, a substantial portion of liquid hydrogen is lost throughout the supply chain, highlighting the need to optimize storage and transportation to ensure energy efficiency. Lessons from the usage of LNG (liquefied natural gas) as a fuel in ports and ships can inform the development of hydrogen-powered ships. While storing more and colder liquid than LNG will be necessary for hydrogen ships [57], the intricacies are more complex due to liquid hydrogen being approximately 90 °C colder and having a lower energy density. Challenges related to sloshing of liquid hydrogen within tanks and its potential impact on ship stability also come to the fore [58]. Ultimately, the choice between different hydrogen storage approaches is a multifaceted decision, requiring a meticulous assessment of operational requirements, safety considerations, energy efficiency, and feasibility within the maritime context. Each method presents a distinct set of advantages and challenges that must be navigated to ensure the successful integration of hydrogen energy in ships.

In the realm of hydrogen storage for ships, four prominent technical avenues with promising development potential have emerged: organic liquid hydrogen storage, methanol reforming to hydrogen, metal hydrolysis to hydrogen, and alloy hydrogen storage. Each of these routes presents distinct advantages and challenges, contributing to the growing portfolio of options for effective hydrogen utilization in maritime applications. Table 3 shows the typical hydrogen storage methods.

The four aforementioned marine hydrogen storage systems have all demonstrated their capacity to meet the essential benchmarks of safety and reliability, thus rendering them suitable for the utilization of hydrogen energy as a power source for maritime applications. However, it is imperative to underscore that the security aspect of employing hydrogen for marine fuel cells is also a crucial area under scrutiny and evaluation.

3.2. High pressure and liquid hydrogen storage methods

3.2.1. High pressure hydrogen storage

Among the various hydrogen storage systems, high-pressure gaseous hydrogen storage and low-temperature liquid hydrogen storage stand as the most established and secure options. These systems have demonstrated reliability and safety in the maritime context. Here are the key characteristics and examples of these storage systems:

High-Pressure Gaseous Hydrogen Storage:

High-pressure storage involves containing hydrogen gas under elevated pressures within specially designed vessels. This method offers practicality and efficiency for storing gaseous hydrogen. Several types of high-pressure hydrogen storage vessels include:

Type I Pure Steel Metal Tank: These pressure vessels are entirely constructed from metal, providing robustness and durability.

Type II Steel Liner Fiber-Wound Tank: This type combines a steel liner and a polymer layer wrapped around a metallic tank, enhancing structural integrity.

Type III Aluminum Liner Fiber-Wound Tank: Type III tanks feature a metallic liner encased within composite fiber layers, ensuring both strength and weight efficiency.

Type IV Aluminum Alloy Liner Fiber-Wound Tank: Type IV tanks utilize a polymer liner enveloped in composite fiber materials. They are lighter in weight compared to type I and type II vessels [57,58]. They are more efficient in terms of gravimetry without the need for a metal vessel body, but the system has less heat resistance as a result [61].

It's worth noting that the development of innovative storage technologies is an ongoing process, as evidenced by the introduction of Type V tanks in 2014. Type V tanks are composite tanks that don't require a liner and claim to withstand pressures exceeding 700 bar

Table 3
Below displays a variety of hydrogen storage technology types [59,60].

Hydrogen storage method	Fundamentals	Reaction equation	Technical Features
Storage of organic liquid hydrogen	The reversible chemical reaction with hydrogen gas is carried out by using also-terminated organic molecular materials containing unsaturated C]C double bonds as hydrogen storage carriers to realize the cyclic hydrogenation-dehydrogenation process.	Take N-ethylcarbazole as an example. $C_{14}H_{13}N + 6H_2 \rightarrow C_{14}H_{25}N + Q$ $C_{14}H_{25}N \rightarrow C_{14}H_{13}N + 6H_2 + Q$	High density of hydrogen storage. Safe and convenient storage, transportation and replenishment. High purity of hydrogen and no tail gas emission. Reusable liquid hydrogen storage carrier material.
Methanol reforming to hydrogen	The catalytic reforming of methanol, ethanol, diesel and other hydrogen-rich fuels to H_2 and CO_2 under certain temperature and pressure conditions in the presence of a catalyst	Main Reaction : $CH_3OH(g) + H_2O(g) \rightarrow CO_2 + 3H_2$ $(\Delta H_{298} = 49.4KJ/mol)$ Side effects : $CH_3OH(g) \rightarrow CO + 2H_2$ $(\Delta H_{298} = 91KJ/mol)$	High density of hydrogen storage. The mpresence of a small amount of CO in the hydrogen produced. There is CO_2 gas emission
Hydrogen production from metal hydrolysis	High-density metal hydrolysis is a “ready-to-use" safe hydrogen source technology based on the reaction of metals or their hydrides (e.g., magnesium hydride (MgH_2)) with water to produce hydrogen.	$MgH_2 + 2H_2O \rightarrow Mg(OH)_2 + 2H_2$ $(\Delta H_{298} = 277KJ/mol\,H_2)$	High density of hydrogen storage. Good safety and reliability of hydrogen production process. High mpurity of hydrogen production.
Alloy hydrogen storage	Hydrogen gas undergoes physical adsorption, chemisorption and decomposition processes on the surface of metal alloy hydrogen storage materials. The hydrogen then diffuses and migrates in atomic form in the hydrogen storage alloy to reach equilibrium, and is finally stored in the lattice interstices with the hydrogen storage alloy and chemically combined with the atoms of the hydrogen storage alloy to generate stable hydrides	$M + H_2 \leftrightarrow MH_2 + Q$ (M: Hydrogen storage materials , Q : Heat of Reaction)	High technological maturity and proven safety and reliability. Fast dynamic response. The hydrogen storage density is not high enough, and new hydrogen storage material system needs to be developed

[62]. However, their adoption remains limited in practical applications [63]. In terms of vessel types, both Type III and Type IV bottles offer improved mass hydrogen storage density compared to Type I and Type II bottles, and they exhibit a lower risk of hydrogen embrittlement. The selection of the most appropriate storage system depends on factors such as vessel weight, hydrogen storage density, safety considerations, and the specific requirements of maritime operations. For a visual representation of the four different types of hydrogen storage tanks, you can refer to Fig. 3 in the relevant literature or resources related to hydrogen storage technologies. Table 4 shows that typical hydrogen storage tanks.

3.2.2. Liquid hydrogen storage technology

The cryogenic liquid hydrogen storage method offers distinct advantages, primarily driven by its high hydrogen storage density per unit volume. Liquid hydrogen boasts a density approximately 845 times that of hydrogen at standard atmospheric pressure. This high density translates to smaller container sizes and a higher storage capacity. However, despite its favorable storage density, the process of liquefying hydrogen involves significant energy consumption, accounting for roughly 30 % of the energy contained in the hydrogen itself [65]. Several key considerations accompany the use of cryogenic liquid hydrogen storage:

Energy Intensity: The energy-intensive nature of hydrogen liquefaction underscores the need for efficient energy sources and processes to minimize energy losses during storage.

Safety Challenges: Liquid hydrogen is highly flammable, necessitating stringent safety measures and protocols. Storage containers must meet rigorous safety standards to mitigate potential risks.

Technology Development: The design and components of liquid hydrogen storage tanks pose challenges, often resulting in higher costs. Further research and development are required to optimize these systems.

While high-pressure gaseous hydrogen storage systems are utilized in hydrogen-powered vehicles, such as the Toyota Mirai's 3-layer hydrogen storage tank [66], the cryogenic liquid hydrogen storage technology holds promise for maritime applications. Its advanced technology and successful implementation in commercial vehicles make it a potential candidate for hydrogen storage on ships. The progress of hydrogen energy ships and their eventual industrialization and commercialization hinges on the assurance of secure hydrogen storage systems. However, hydrogen storage presents challenges related to leakage and material compatibility. Hydrogen's rapid dispersion in the atmosphere, coupled with its lightweight and small molecular diameter, can result in leakage. Additionally, prolonged exposure to hydrogen can adversely affect certain metal materials, diminishing their service life and raising safety concerns. Hydrogen embrittlement, wherein hydrogen atoms infiltrate materials under high-pressure conditions, poses another challenge to material integrity. Addressing these challenges and ensuring the safety and reliability of hydrogen storage systems is pivotal for realizing the potential of hydrogen energy in maritime applications. As evident from Table 5, various national standards papers outline testing procedures and standards to evaluate hydrogen embrittlement, emphasizing the importance of thorough and standardized assessment in this field.

3.3. Three common hydrogen storage safety issues

1. **Hydrogen Embrittlement:** Hydrogen embrittlement is a phenomenon that occurs over an extended period, resulting in a decrease in the mechanical properties of metallic materials. This effect poses a significant threat to the safety and integrity of hydrogen storage and delivery systems. Failure of containers due to hydrogen embrittlement can have catastrophic consequences for the surrounding environment. Various factors contribute to the development of hydrogen embrittlement, including hydrogen concentration, ambient temperature, exposure duration, stress levels, and material composition. Research by Meng et al. [71] delved into the properties of pipeline steel materials under different hydrogen concentrations. The findings indicated that higher hydrogen concentrations correlated with increased susceptibility to hydrogen embrittlement. Amaro et al. [72] developed a model to predict the propagation of fatigue cracks in pipeline steels when subjected to high-pressure gaseous hydrogen environments. This research aids in understanding the effects of hydrogen on material fatigue behavior. Komoda et al. [73] explored the impact of carbon

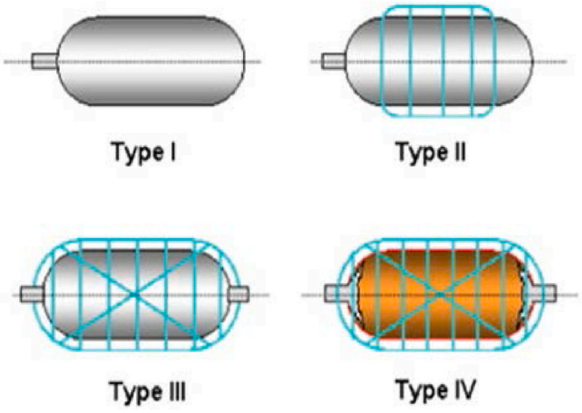

Fig. 3. Different types of hydrogen tanks [7].

Table 4
Compares the traits and uses of the four different types of hydrogen storage tanks [64].

Types	Materials	Features	Applications
Type I	All metal (steel) tanks	Heavy, internal corrosion, low hydrogen storage density	For industrial, not suited for vehicular use
Type II	Metal liner with hoop wrapping	Heavy, short life due to internal corrosion	Not suited for vehicular use
Type III	Composites (carbon fiber) with inside metal liner (Al or steel)	Lightness, high burst pressure, no permeation, galvanic corrosion between liner and fiber	Suited for vehicular use, 25–75 % mass gain over I and II
Type IV	Plastic liner with full composite wrapping	Lightness, lower burst pressure, Permeation though liner, high durability against repeated charging	Longer life than Type III (no creep fatigue), cheaper.

Table 5
Sample national standard documentation for tests related to hydrogen embrittlement.

Scope of use	Code Name	Name
International Standards	ISO 11114–4：2017	Mobile Gas Cylinders - Compatibility of Cylinder and Valve Materials with Contained Gases [67]
U·S. Standards	ASME-BPVC-VIII-3 KD-10	Special Requirements for Pro-Hydrogen Containers" [68]
U·S. Standards	ASTM G142-98	Standard Test Methods for the Compatibility of Metallic Materials with the Hydrogen Environment under High Pressure or High Temperature Conditions [69]
China Standards	GB/T 34542.2–2018	Hydrogen Storage and Transport Systems - Part 2: Test Methods for the Compatibility of Metallic Materials with the Hydrogen Environment [70]

monoxide impurities present in hydrogen on the accelerated growth of fatigue cracks in pipeline steels. The study contributes to strategies for mitigating the occurrence of hydrogen embrittlement. Michler et al. [74] reported that aluminium alloys exhibit resistance to the dry, high-pressure hydrogen environment, making them a potential choice for hydrogen storage vessels due to their reduced susceptibility to embrittlement. Certain austenitic stainless steels with high chromium (Cr) and nickel (Ni) ratios display enhanced resistance to high-pressure hydrogen embrittlement [75], making them suitable candidates for materials that interact with hydrogen. Hwang et al. [76] demonstrated that utilizing polytetrafluoroethylene (PTFE) coatings can enhance the resistance of austenitic stainless steels used in liquid hydrogen tanks to hydrogen embrittlement. Understanding and mitigating hydrogen embrittlement are critical for the safe and reliable deployment of hydrogen storage systems. Researchers are actively exploring material choices, impurity effects, and protective coatings to address this challenge and ensure the integrity of hydrogen-related infrastructure.

2. **Hydrogen Permeation:** Hydrogen permeation is a significant concern in the context of hydrogen storage systems. While it is not a prominent issue for Type I, II, and III pressure vessels, it becomes a safety consideration for Type IV pressure vessels with non-metallic linings exhibiting high hydrogen permeability. The extent of hydrogen permeation can have implications for vessel safety and longevity. Permeation in Type IV Vessels: Type IV pressure vessels with non-metallic linings, particularly those utilizing carbon fiber overwraps, can experience hydrogen permeation issues, especially as they approach the end of their service life. Microcracks that develop over time can compromise the resin/carbon fiber matrix, leading to increased hydrogen permeation. Causes of Lining Failure: Wang et al. [77] conducted an in-depth exploration of lining failure causes, encompassing hydrogen permeation, thermal instability, and mechanical damage. Their study focused on devising optimization strategies involving alternative materials. Polyamide emerges as a promising candidate for Type IV hydrogen storage tanks due to its robust molecular polarity and hydrogen bonding properties. Polyamide as a Liner: Sun et al. [78] conducted a comprehensive investigation into the suitability of polyamide filled with laminated inorganic components as a liner for hydrogen storage tanks. Their findings revealed a notable reduction (3–5 fold) in hydrogen permeability, suggesting the viability of this material as a hydrogen barrier. However, the study did not delve into the effects of gas cycling on material properties like hydrogen permeability. Composite Solutions: Novel composite materials are also being explored to address hydrogen permeation concerns. Highly gas-resistant polyethylene composites containing non-graphene oxide flakes and carbon fiber-graphene hybrid composites hold promise for lightweight high-pressure gas storage containers [79,80]. These materials show potential for enhancing hydrogen retention and safety. Managing hydrogen permeation is essential to ensure the safety and effectiveness of hydrogen storage systems. Researchers are investigating various materials and composite solutions to mitigate permeation issues and enhance the performance of hydrogen storage vessels, particularly those with non-metallic linings.
3. **Failure of Composite Materials:** Understanding the failure mechanisms of composite fiber materials is of paramount importance, as these materials bear the primary load in hydrogen storage tanks. Ensuring the structural integrity of these materials is essential to prevent accidents and ensure the safety of hydrogen storage systems. Finite element techniques are commonly employed to predict the damage properties and strength of composite materials. Wang et al. [81] devised a progressive damage model using ABAQUS to forecast the ultimate load carrying capacity and intricate failure behavior of composite Al-CF/epoxy vessel structures. Liu et al. [82] conducted a comparative analysis of two distinct failure mechanisms for composite containers: intra-laminar damage and inter-laminar peeling. They determined that intra-laminar damage primarily influences the mechanical properties of composite containers. Chang et al. [83] employed finite element analysis to assess the structural integrity of a Type III hydrogen pressure

vessel subjected to impact loading. Their study revealed that even if certain layers experienced transverse failure due to delamination or matrix failure, the overall structure remained safe during service conditions and subsequent impacts. Chou et al. [84] proposed a model to predict the accumulation of fiber fractures in advanced composites. They demonstrated that damage to the unidirectional composite structure can lead to the formation of random fiber fractures. Future research should encompass theoretical, simulation, and experimental investigations of tank failure during repeated filling under realistic operational conditions. This will provide insights into the behavior of composite materials over time and enable the development of strategies to enhance the durability and safety of hydrogen storage tanks. Understanding and mitigating the failure mechanisms of composite materials is vital for ensuring the reliability, durability, and safety of hydrogen storage vessels. Researchers are employing advanced modeling techniques to predict failure behavior and exploring ways to enhance the performance and resilience of composite structures in hydrogen storage systems.

3.4. *Refilling mechanism*

The rapid filling of high-pressure hydrogen storage tanks can lead to significant pressure and temperature increases (up to 70 MPã80 MPa) [85], potentially causing tank failure, and the short filling time results in a significant increase in hydrogen temperature, which may lead to tank failure. Understanding the mechanisms behind temperature increase during refueling is crucial for proposing effective refueling strategies that maintain safety and hydrogen storage mass. Among various turbulence models, the shear stress transfer model and the Reynolds stress model are considered more accurate for predicting the behavior of compressed gas in high-pressure tanks [86]. Wang et al. [87] identified filling rate, initial tank pressure, and hydrogen inlet temperature as key factors affecting filling quality. They found that reducing the filling rate and inlet temperature could improve hydrogen quality. Guo et al. [88] conducted gas charging and discharging experiments, proposing a model to describe the thermal behavior during cyclic tests. They investigated the effects of factors such as ambient temperature, filling temperature, start-up method, filling time, and filling flow rate on temperature variation. To address temperature rise effects, Zhang et al. [89] suggested measures such as pre-cooling of hydrogen, staged filling, controlling filling rate, and selecting suitable lining materials for hydrogen storage tanks. Wu et al. [90] introduced time-delayed filling strategies that significantly reduced filling time under normal conditions. This approach saved 62 % of the time compared to constant mass flow filling. Li et al. [91] explored using a filler with high porosity (97 %) to suppress heat transfer in the tank. However, an excessive amount of filler may slow down gas flow excessively and lead to thermal stratification, prompting the need for further investigation into filler design for more effective solutions. While microtubular hydrogen storage shows promise, there are unknown characteristics, such as the flow process during hydrogen filling. Given the small diameter and length of microtubes, filling time and mechanical damage from high temperature and pressure are critical factors for successful application. Research is focused on understanding and managing temperature increases during rapid filling to ensure the safety and efficiency of hydrogen storage systems. Various strategies, from modeling to time-delayed filling and innovative filler designs, are being explored to mitigate temperature-related challenges during hydrogen refueling.

3.5. *Hydrogen leak dispersion and safety study*

The distinction between the two types of hydrogen leak jets is based on the ratio of the hydrogen leak source pressure to the ambient atmospheric pressure. These types are described as follows:

Subacoustic Jet: In this type of jet, the hydrogen jet fully expands at the outlet, and its pressure becomes equal to the ambient pressure. The flow velocity of the jet is slower than the local sound velocity in the surrounding medium.

Non-Fully Expanded Jet: In this type of jet, the hydrogen gas continues to expand after it exits the leak, creating a burst or surge of gas. The flow velocity at the outflow is equal to the local sound velocity in the surroundings.

These two types of hydrogen leak jets are characterized by their pressure levels, flow velocities, and expansion behaviors as they interact with the ambient atmosphere. The distinction between the fully expanded subacoustic jet and the non-fully expanded jet with a surge has implications for the behavior of hydrogen leaks and their potential hazards. The jet gas continues to grow outside the leak, generating a surge, as shown in Fig. 4. The flow velocity at the outflow is equal to the local sound velocity.

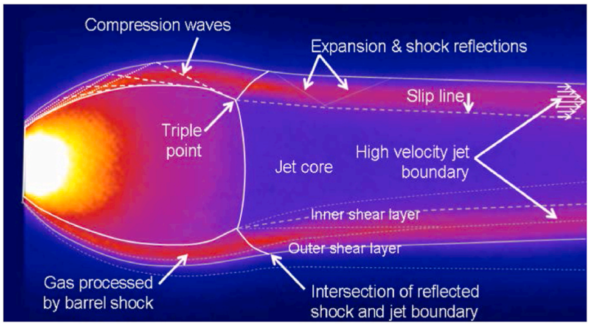

Fig. 4. Excitation structure of under-expanded jet [92].

Numerous scientific inquiries have delved into the realm of hydrogen jet flames, given the potential of hydrogen leaks to spontaneously ignite or give rise to jet flames upon ignition. Yet, the under-expansion jet dimensionless flame length's correlation with the Reynolds number remains elusive in its ability to accurately recreate such scenarios. Molkov et al. [93] discerned its inapplicability to under-expansion jets, partly due to the intricate interplay of non-ideal hydrogen behavior at high pressures, friction, and minuscule losses during leakage. The original hypothesis of under-expansion jets, contingent on the Reynolds number, emerged, considering these variables. To mitigate the effects of jet flames and minimize overall damage, the San Diego National Laboratory examined barrier utilization through simulated and integrated experimental research [94]. Kuznetsov et al. [95] probed the structure and flame propagation mechanisms of hydrogen jets across various temperatures and jet nozzle diameters. They revealed that turbulence intensity influences flame propagation, even within hydrogen's flammability-limited zone, leading to a stable jet flame. Despite a multitude of investigations on hydrogen jet flames, there persists a dearth of comprehensive combustion and thermal radiation models. Leaked hydrogen gas fosters enrichment and, in tandem with oxygen, begets combustible clouds. The ensuing jet flame can undergo diverse transitions, ranging from gradual combustion to inadvertent detonation. Wang et al. [96] executed both experimental and simulation-based explorations on high-pressure hydrogen injection until detonation materializes. Deflagration, an initial combustion phase where the combustion wave's speed is eclipsed by the shock wave's, holds significance in Deflagration-to-Detonation Transition (DDT). This progression accentuates accident ramifications, marking a pivotal focus in hydrogen combustion and explosion safety research. Acceleration of the combustion wave to meet the shock wave's pace exacerbates the DDT process, underlining its complex dynamics and uncharted attributes. Giannissi et al. [97] harnessed 28 sets of experimental data to scrutinize hydrogen leakage and diffusion under natural ventilation conditions. Numerical outcomes from diverse CFD-based programs (including ANSYS CFX, ADREA-HF, and ANSYS Fluent, utilizing the k-model and large eddy model) were juxtaposed against the experimental findings. Insights into explosion overpressure and flame propagation velocity, correlating with hydrogen concentration, were gleaned from these analyses, unveiling the potential for increased overpressure and flame velocity due to turbulence resulting from barriers. Sato Y et al. [98] embarked on detonation tests within a 37 m^3 rectangular chamber and a 300 m^3 hemispherical chamber, varying hydrogen content from 15 % to 57 %. Leakage was assumed to arise from deteriorating hydrogen supply pipes with a 10 mm bore diameter. In a separate study, Takeno et al. [99] investigated induced leakage, diffusion, and explosion within a 40-MPa hydrogen cylinder. Varying ignition times post-leakage yielded insights into hydrogen's explosive potential, determined by premixed concentration and turbulence characteristics. This comprehensive exploration into hydrogen jet flames and associated phenomena collectively advances our understanding of combustion dynamics and safety considerations, contributing substantially to the evolving field of hydrogen-related research.

Furthermore, meticulous attention must be directed towards the selection of appropriate piping materials and original components within the hydrogen power system. These elements necessitate specific characteristics such as explosion-proof, anti-static, and flame

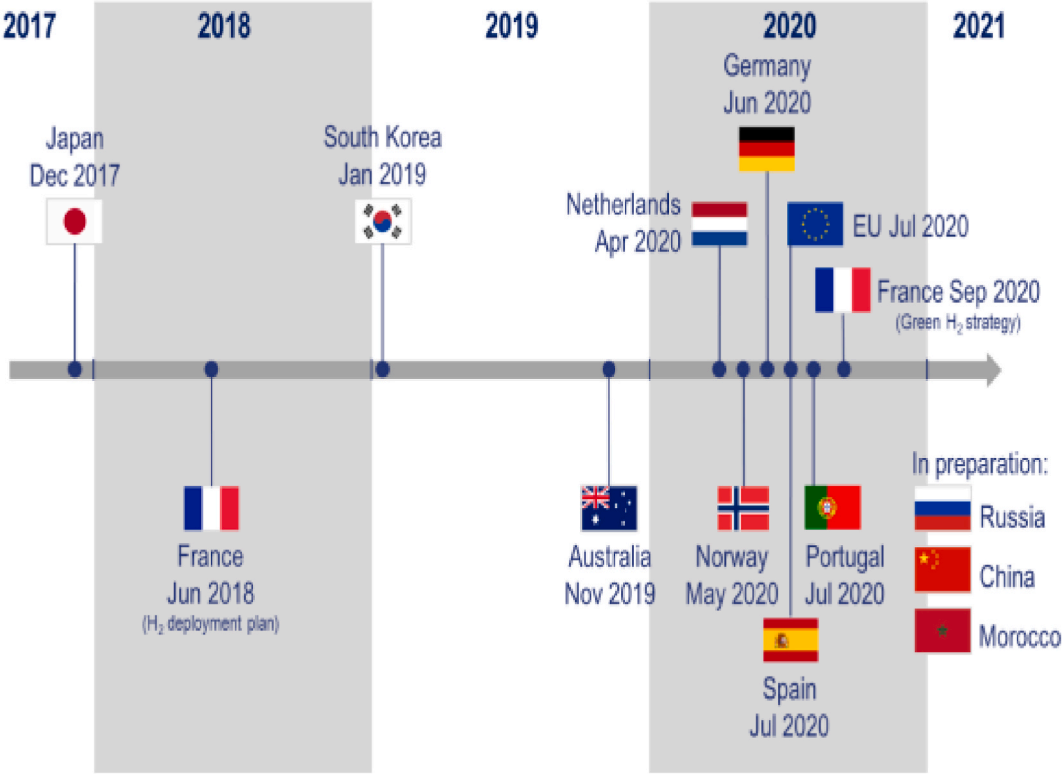

Fig. 5. Timeline of analyzed national hydrogen strategies publication [101].

retardant properties. This selection is imperative to avert any potential ignition of hydrogen gas due to circuit sparking during operation, or even the occurrence of spontaneous combustion or explosions resulting from high-pressure injections. In the context of marine applications, an additional criterion surfaces—the chosen materials must exhibit high resistance to salt spray corrosion. Considering the maritime environment, it is equally crucial to establish comprehensive collision protection protocols for the hydrogen vessel, mitigating the risk of marine emergencies. Intricate deliberation should guide the arrangement of each component within the hydrogen ship. Factors including the type of component, its intended function, and the ship's scale ought to be meticulously considered. To address the dynamic operational conditions of the ship, aside from specialized fixed brackets and supporting steel belts, the integration of buffer facilities becomes essential. These provisions will effectively absorb the frequent oscillations that accompany ship operations, promoting stability. In order to comprehensively manage an array of complex scenarios arising from collisions, the installation of multiple inertia switches throughout the vessel becomes paramount. This network of inertia switches functions as a preemptive measure, enabling the control system to swiftly respond to unfavorable conditions. Consequently, this swift response empowers the system to promptly terminate the hydrogen supply, concurrently maintaining a minimal level of hydrogen leakage. Harmonizing these aspects seamlessly amalgamates safety, operational efficiency, and adherence to maritime standards, thus fortifying the overall viability of hydrogen-powered maritime ventures.

3.6. The development status and policy direction of countries around the world

The global shift towards achieving carbon neutrality is rapidly gaining momentum. In this transformative journey, hydrogen energy has emerged as a pivotal player. Esteemed for its environmentally friendly attributes, low carbon footprint, ample availability, and its role as a versatile secondary energy source, hydrogen energy is undergoing an unprecedented evolution. It has swiftly evolved into a cornerstone, holding the potential to facilitate extensive and profound decarbonization across various sectors, particularly transportation. Within the broader context of emissions, ships contribute to approximately 4.5 % of the global carbon emissions pie [100]. To contextualize the global push for hydrogen energy, refer to Fig. 5, which succinctly outlines the comprehensive policy framework governing hydrogen energy on a global scale. Noteworthy nations and regions such as Germany, the United States, China, Japan, and South Korea, have taken resolute steps by formulating national strategies devoted to the advancement of hydrogen energy. These strategies encompass not only the research and development of hydrogen energy but also extend to the nurturing of fuel cell technologies and their industrial applications. The confluence of these efforts underscores the collective commitment to a sustainable and green energy paradigm. By embracing hydrogen energy, the global community aspires to address the imminent challenges posed by carbon emissions and hasten the transition towards a cleaner, more sustainable energy landscape. This unified drive towards hydrogen energy encapsulates the collaborative determination to forge a future marked by enhanced environmental stewardship and energy sustainability. As shown in Fig. 5 below, which summarizes the global hydrogen energy policy framework, numerous nations, and regions, including Germany, the United States, China, Japan, and South Korea, have designated national hydrogen energy development strategies to actively develop hydrogen energy and fuel cell technology research and industrial development.

3.6.1. Europe: Smart cultivation of hydrogen power

Europe has taken a proactive stance in the realm of low-emission alternative energy solutions for maritime transportation. This proactive approach has been coupled with substantial policy initiatives and funding directed towards supporting green ship endeavors. Consequently, these efforts have not only spurred innovation but also elevated the level of ingenuity within the maritime sector. Norway stands out as a pioneering force in the realm of hydrogen-fueled ships. Meanwhile, the European continent as a whole has assumed a leadership role in advancing the research and practical application of hydrogen-fueled ships. The region has spearheaded numerous pivotal hydrogen-fueled ship initiatives, cementing its status as a vanguard in this transformative domain. Among European nations, Norway has taken noteworthy strides in advocating for hydrogen fuel adoption within maritime transport. This concerted effort has led to the development of a comprehensive and well-structured model for the widespread use of hydrogen as a propulsion fuel in maritime applications. One prominent endeavor is the “HySHIP" project, which has garnered financial backing from governmental and specialized funding sources. The objective of this initiative is to drive down the developmental and operational costs associated with transitioning to liquid hydrogen as a ship propulsion fuel across Europe. The project involves the design and construction of a demonstration roll-on/roll-off (ro-ro) ship, powered by green liquid hydrogen. Central to its mission is the establishment of a robust liquid hydrogen supply chain and a dependable fuel supply platform. Distinguishing itself with a unique approach, the HySeas III project utilizes surplus renewable energy to produce hydrogen. This approach sets it apart from other projects by integrating innovative design solutions hinged on novel energy considerations. Further contributing to the advancement of hydrogen energy in maritime transport, a consortium of 26 prominent companies and associations has collaborated to release the Hydrogen-Fueled Ships Manual [102]. Released in June 2021, this practical manual serves as a blueprint for future regulatory frameworks governing hydrogen energy implementation on ships. Spearheaded by Europe and the United States, this coalition includes esteemed entities like DNV, Air Liquide, Linde, Kawasaki, Chatter Industries, Pike, Ballard, and Cummins, with several others listed as Phase I observers, all collectively engaged in the developmental process. These collective endeavors underscore Europe's resolute commitment to ushering in a new era of sustainable maritime transport, marked by advanced energy solutions and collaborative partnerships.

As Europe propels itself into the exploration and funding of novel ship projects, a surge in the responsibilities shouldered by governmental agencies and research institutions becomes evident. Within this dynamic framework, hydrogen-powered ships stand as emblematic examples of the burgeoning era of environmentally conscious vessels. These ships, intertwined with the intelligent enhancement of energy efficiency, epitomize Europe's commitment to advancing hydrogen-fueled ships in both their developmental and operational phases. A pivotal aspect that underpins the progress of hydrogen-fueled ships in Europe is the tight integration of these vessels with the overarching goal of energy use efficiency enhancement. The convergence of these objectives serves as a driving force propelling the development and deployment of hydrogen-powered ships. It's worth emphasizing that Europe's primary focus regarding hydrogen-fueled ships lies in their application within inland and offshore waters. The practicality of realizing tangible benefits becomes more apparent in these contexts due to several factors. The energy density of hydrogen fuels, coupled with the nascent stage of their application, presents a challenge for larger vessels to achieve quantifiable advantages. This is not to say that larger ships won't eventually see benefits, but early stages of implementation may pose hurdles. A critical factor that enables Europe's enthusiastic pursuit of hydrogen-fueled ships in these specific environments is the extensive network of waterways. The presence of hydrogen refueling stations in most ports, catering to both trucks and ships, fortifies the feasibility of utilizing hydrogen as a fuel source. Additionally, the maneuverability and ease of berthing for smaller ships further amplify the viability of adopting hydrogen propulsion. In essence, Europe's strategic approach revolves around a holistic synergy that unites hydrogen-fueled ships with the larger vision of bolstering energy efficiency. This alignment not only accelerates the progression of these ships but also underscores Europe's dedication to cultivating a greener, more sustainable future for maritime transportation.

3.6.2. Japan and South Korea: vying for "international standards"

Japan has adopted a distinct focus in its pursuit of hydrogen-powered ships, centering its efforts on the development of large ocean-going vessels. This stands in contrast to Europe's emphasis on smaller hydrogen-powered ships. In accordance with Japan's Ministry of Economy, Trade and Industry (METI), the timeline for the commercialization of zero-emission ships is projected to span from 2025 to 2030 [103]. A sweeping transformation is anticipated, with all presently conventionally-fueled ships transitioning to utilize low-carbon fuels—such as hydrogen, ammonia, and liquefied natural gas (LNG)—by the year 2050. As a part of Japan's comprehensive strategy, the advancement and implementation of electric propulsion systems and hydrogen fuel cell systems are championed for shorter-range, compact vessels. This underscores Japan's proactive approach in promoting these environmentally friendly technologies within maritime transportation. Simultaneously, a deliberate drive is underway to foster the development and incorporation of ammonia and hydrogen fuel engines. This initiative pertains primarily to long-range, larger ships. The endeavor encompasses not only the engines themselves but also entails the creation of compatible fuel tanks and the requisite fuel delivery systems. Japan's commitment extends beyond national boundaries, as it actively engages in the formulation and revision of international codes and standards for ship fuel performance. This collaborative engagement transpires within the framework of the International Maritime Organization (IMO), underscoring Japan's dedication to influencing and shaping global maritime standards. In essence, Japan's strategic direction is geared towards the establishment of a comprehensive, eco-conscious maritime ecosystem. Through the integration of innovative technologies, proactive policy frameworks, and active participation on the global stage, Japan is poised to catalyze substantial progress towards a more sustainable and environmentally responsible maritime industry.

In March 2021, Korea Shipbuilding & Marine, a subsidiary of the Hyundai Heavy Industries Group responsible for shipbuilding, made a significant announcement. The company revealed that it had entered into a business cooperation agreement with the Korea Classification Society (KR) to collaboratively develop a comprehensive hydrogen ship design and safety code. This endeavor aims to address critical aspects concerning gas storage, fuel supply systems, cargo handling systems, and other pertinent elements for ships powered by hydrogen. By the close of 2022, the company has set a notable goal: to present the International Maritime Organization (IMO) with the inaugural hydrogen ship specification standard. This initiative marks a crucial step in the direction of formalizing international guidelines and standards for the burgeoning field of hydrogen-powered maritime vessels. The strategic impetus behind these efforts is further reinforced by Hyundai Heavy Industries' financial allocation. The infusion of $720 million from the KKR Group is earmarked explicitly for investments in two pivotal domains: artificial intelligence (AI) and hydrogen-powered ships. This deliberate capital allocation underscores Hyundai Heavy Industries' commitment to advancing innovation at the intersection of AI and clean energy solutions within the maritime industry. In essence, these collective initiatives exemplify a comprehensive and forward-looking approach, with a focus on both technological innovation and regulatory standards. By forging collaborations, contributing to global regulations, and strategically investing in promising fields, Hyundai Heavy Industries is positioning itself as a trailblazer in the evolution of the maritime sector towards more sustainable and technologically advanced practices.

3.6.3. China: major technical difficulties

China has leveraged national-level initiatives to propel the advancement of hydrogen-powered ships within its maritime industry. This concerted effort is underscored by tangible progress in crucial areas like hydrogen fuel cell research and development, offering concrete evidence of China's exploration of hydrogen energy applications in the maritime sector. Of notable significance is China's focus on Carbon Capture and Storage (CCS), a pivotal domain within hydrogen fuel cell regulations for ships. The Chinese Classification Society (CCS) has emerged as a key player in this field, conducting comprehensive research to establish regulations governing hydrogen fuel cells for maritime use. The culmination of these efforts has resulted in the formulation of safety technical benchmarks encompassing fuel cell ship layout, system design, fuel storage, and auxiliary refueling systems. The pivotal guidelines outlined in CCS's "Guide to the Application of Alternative Fuels for Ships," published in 2017, serve as a cornerstone for regulating hydrogen fuel cells. Furthermore, CCS has actively embarked on an array of engineering practices and application-focused research, centered on the fundamental technologies of hydrogen fuel cell ships. This sustained endeavor has yielded substantial advancements across safety design, hydrogen storage, refueling mechanisms, and hydrogen utilization. Significantly, CCS has surmounted intricate technical hurdles, spanning the domains of overall design, system design, equipment manufacturing, standard development, and risk assessment related to hydrogen fuel applications in ships. The accumulation of an extensive dataset derived from actual measurements has provided Chinese shipbuilders with a critical theoretical underpinning and empirical foundation for their subsequent hydrogen fuel cell designs. China's multi-faceted approach, encompassing regulatory frameworks, research, practical applications, and risk assessment, testifies to its dedication to nurturing a robust ecosystem for hydrogen-powered ships. This multifarious effort coalesces into an advantageous position for Chinese shipbuilders, driving progress towards the realization of hydrogen-powered maritime vessels, while bolstering the nation's credentials as a pioneering force in the maritime energy transition.

In China, the evolution of hydrogen energy and fuel cell technology standards has reached a mature stage within the realm of land-based applications. In contrast, the domain of marine fuel cell technology standards is still in a developmental phase. As of now, relevant fuel cell systems and hydrogen storage and refueling systems predominantly draw upon existing land-based standards. A significant milestone was reached with the release of the "Outline for the Construction of a Strong Transportation Nation" by China's State Council in September 2019. This strategic document outlines China's ambitious aspiration of establishing itself as a formidable logistics powerhouse. To realize this vision, the document extends substantial policy support and notable incentives to the hydrogen energy industry. The comprehensive approach enshrined in the "Outline" encompasses diverse aspects, including the expansion of hydrogen energy infrastructure, the electrification of urban logistics systems, and the adoption of new energy solutions in ship transportation. Each of these pillars reflects China's holistic commitment to fostering a sustainable, efficient, and environmentally

Table 6
Typical hydrogen fueled vessels in the world [104–106].

Serial number	The name of the ship	Participating organizations	Particular year	Mechanical system	Vessel Basic Information
1	Lihu Ship	Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian Maritime University	2021	70 kW hydrogen fuel cell stacks and 84 kW h lithium batteries make up the hybrid drive	China's first fuel cell yacht, 13.9 m long, with a design speed of 18 km-h, a range of 189 km, and 10 passengers.
2	Energy Observer	Toyota, Corvus Energy	2020	Hybrid system consisting of solar photovoltaic, wind power and fuel cells, with 126 kW hydrogen fuel cells and 168 m^2 of solar panels on board	Boat length 30.5 m, width 12.8 m, total mass 28t, speed 11Kn
3	Hydrovolle	Compagnie Maritime Belge (CMB)	2017	2 × 441 kW diesel/hydrogen dual-fuel internal combustion engines; including 12 x 205 L hydrogen tanks (20 MPa) and 2 x 265 L fuel tanks.	Length 14.0 m, Breadth 4.2 m, Draught 0.65 m, Maximum Speed 27Kn, Average Speed 22Kn, Gross DWT 14t
4	Nemo H_2	Rederij Lovers	2012	The power system includes 2 sets of 30 kW PEMFC and 1 set of storage battery, the output power is 70 kW, using 35 MPa high-pressure hydrogen storage method, hydrogen storage capacity of 24 kg.	Passenger boat length 24.9 m, width 4.2 m
5	Hornblower Hybrid	Hornblower	2012	The power system consists of a 32 KW PEMFC, two 5 kW wind turbines, and a 20 kW solar photovoltaic array, which together with the diesel generators provide hybrid power for the vessel	Boat length 11.0 m, width 3.6 m, passenger capacity 14 (including crew 2), speed 6~10kn
6	Hydrogenesis	Bristol Bost Trips	2012	4 fuel cells provide 12 kW of power, hydrogen is stored in 350 bar tanks, fuel cell Charging time is 10min	The ship's length is 11.0 m, width is 3.6 m, passenger capacity is 14 persons (including 2 crew members), speed 6~10kn
7	Ms Forester	Thyssen Krupp Marione Systems、 DNV	2009~2017 2017~2022	Installation of 100 kW SOFC fuel cell system As an auxiliary power, the SOFC fuel cell can Hydrogen, methanol, etc. are used as fuel	Length 92.5 m, width 17.0 m
8	Ms Mariella	Meyer Werft、 DNV	2009~2017 2017~2022	2 × 30 kW modular HTPEM fuel cells are installed as auxiliary power. The HTPEM fuel cell can The HTPEM fuel cell can be fueled by hydrogen, methanol, etc.	Length 177.0 m, width 28.0 m. Carrying 2500 passengers
9	Alsterwasser	Proton Motors、GL、Alster Tourisrik	2006~2013	Equipped with 2 × 50 kW PEMFC fuel cells and 120Ah colloidal lead-acid battery, using 35 MPa compressed hydrogen, hydrogen storage capacity 24 kg	The ship is 25.5 m long, 5.4 m wide, with a draft of 1.33 m. Maximum speed 8kn, over 100 passengers.
10	Viking Lady	Wallenius Maritime、Wartsila、DNV	2003~2010	A 320 kW Molten Carbonate Fuel Cell (MCFC) was installed. (Molten Carbonate Fuel Cell (MCFC)) system is installed as an auxiliary power system. The MCFC fuel cell can use hydrogen, methanol, etc. as fuel.	The ship's length is 92.0 m, width is 21.0 m, gross deadweight tonnage is 6100t. 6100t, 25 passengers, can hold 993m^3 of fresh water and 167m^3 of methanol.
11	Ms Weltfrieden	Lioyd	2000	Converted for touring buses and fitted with a 10 kW powered PEMFC propulsion unit utilizing two metal Hydrogen storage units with a total of 54 cubic meters of hydrogen.	

responsible transportation landscape, while strategically leveraging the potential of hydrogen energy. While the land-based hydrogen standards have achieved maturity, the maritime sector is still adapting and integrating these standards to suit the distinct challenges and opportunities presented by ships. The “Outline" serves as a pivotal guide, steering China’s policies and efforts towards a more sustainable and robust transportation network, bolstered by hydrogen energy, and positioning the nation on the forefront of the global transition towards cleaner energy solutions in transportation.

Guangdong, China’s “Maoming City Hydrogen Energy Industry Growth Strategy (Draft for Comments)," unveiled in March 2020, introduced a comprehensive vision. This strategy explicitly proposed the initiation of trials involving fuel cell applications in ships, combined heat and power systems, and industrial power generation. This strategic document underscores the proactive stance taken by Guangdong in advancing hydrogen technology across multiple sectors. Building on this momentum, China’s Ministry of Transport issued a notable notice titled “Outline of Inland Waterway Shipping Development" in June 2020. Within this directive, a clear roadmap is laid out, emphasizing the promotion of energy-efficient and environmentally friendly LNG-powered ships. The notice also advocates for the exploration of alternative propulsion systems, including fuel cells and pure electric power. The utilization of renewable sources such as solar energy, wind energy, and hydrogen energy is highlighted as part of the industry’s potential. In December 2020, Zhoushan City, Zhejiang Province, released the “Guidance on Accelerating the Cultivation of Hydrogen Energy Industry Development in Zhoushan City." This comprehensive guidance envisions the integration of hydrogen energy in various marine applications, spanning ships, marine transportation, and port logistics. Notably, it introduces the concept of a “Marine Hydrogen Island" as a pioneering endeavor in creating a significant hub for hydrogen energy marine applications. China’s State Maritime Administration further substantiated its commitment to hydrogen-powered ships through a series of regulatory initiatives. In July 2021, the “Interim Regulations for the Technology and Inspection of Hydrogen Powered Ships (Draft for Public Comments)" were introduced. This document represents a pivotal step towards standardizing hydrogen-powered ships’ technology and inspection procedures. A significant milestone followed in March 2022, with the publication of the “Interim Regulations for the Technology and Inspection of Hydrogen Fuel Cell Powered Ships (2022)" by the State Maritime Administration. This rule mandates that all hydrogen fuel cell-powered ships conform to the specified provisions encompassing design, construction, operation, inspection, and testing. These collective initiatives exemplify China’s resolute commitment to leveraging hydrogen energy within the maritime sector. The proactive approach is reflected in a combination of policy initiatives, regulations, and strategic directives. This orchestrated effort underscores China’s pioneering role in the global movement towards greener, more sustainable maritime transportation powered by hydrogen.

Absolutely, the global landscape is witnessing an intense competition among nations to pioneer the development of hydrogen-powered ships, thereby accelerating the pivotal process of decarbonizing maritime transportation. The forthcoming years hold the promise of a transformative shift, with hydrogen-powered ships poised to supplant their diesel-powered counterparts. This transition holds the potential to achieve a profound reduction in greenhouse gas emissions, culminating in the emission of only water from the ship’s hull, rendering them virtually emissions-free. Hydrogen-powered ships not only symbolize a shift towards a cleaner and more sustainable future but also represent a paradigm shift in propulsion capabilities. The utilization of hydrogen as a fuel source bestows ships with enhanced propulsion power, further underscoring the technological advancements and efficiencies associated with this innovative energy solution. The overarching impact extends beyond individual vessels. The widespread adoption of hydrogen-powered ships serves as a catalyst for transforming the maritime industry’s landscape. The transition towards clean energy, galvanized by the popularity of new energy vehicles, has now permeated the maritime domain. As nations work fervently to develop hydrogen technologies, formulate regulations, and foster collaborations, the maritime sector is embarking on a transformative journey towards a greener and more ecologically responsible future. In essence, the global race to create hydrogen-powered ships exemplifies the collective commitment towards reducing carbon emissions and embracing innovative solutions for sustainable maritime transportation. The ensuing era of hydrogen-powered decarbonized ships not only signifies progress but also ushers in a new era of environmentally conscious and technologically advanced maritime endeavors.

At this stage, the power of Marine fuel cell system is generally within 350 kW, and it is developing into a 500–1000 kW fuel cell system. In addition to the completed hydrogen-powered ships listed in Table 6, there are many ongoing hydrogen-powered ship projects in the world, including: DNV’s Thames Hydrogen Eco-project, Samsung Heavy Industries’ collaboration with Bloom Energy’s hydrogen fuel-powered vessel, Norled AS’s hydrogen ferry, The Water-Go-Round hydrogen-powered vessel built by Hydrogenics and Golden Gate Zero Emission Marine (GGZEM), the Viking Sun liquid hydrogen-powered tanker built by Viking Cruises, The SF-BREEZE high-speed passenger ferry built by Sandia National Laboratories in collaboration with Red and White Fleet, the River Cell-Elektra hydrogen-fueled hybrid tugboat carried out by TUBerlin, BEHALA and DNV, And Ustan Group and Nedstack fuel cell technology company jointly built SX190DP2 hydrogen fuel powered sea ships. China Hydrogen ship research: During the 20th China International Maritime Exhibition, China State Shipbuilding Group announced its self-developed hydrogen fuel powered inland self-unloading cargo ship. The length is 70.5 m, the width is 13.9 m, the design draft is 3.1 m, the design speed is 13 km/h, and the endurance is 140 km. A 4 × 125 kW PEMFC fuel cell and a 4 × 250 kW h lithium battery were used as the ship’s dynamic force source, and a total of 280 kg of hydrogen was stored in a 35 MPa high-pressure gas cylinder for hydrogen fuel storage system. It has obtained the basic design AIP certification of 500 kW river hydrogen fuel powered cargo ship issued by China Classification Society.

3.7. Commercialization development of hydrogen ships

International organizations and countries like the EU, Germany, the United States, Norway, China, and Japan are at the forefront of advancing marine hydrogen fuel cell propulsion technology. These entities have not only successfully developed marine hydrogen fuel cell power propulsion systems but are also actively promoting and applying these technologies.

Key players like DNV GL, Kongsberg, Shenli Technology, and the China Ship Power Research Institute have taken proactive measures to outline the industrial synergies arising from both domestic and international hydrogen fuel cell developments. They focus on fostering market-oriented business models, spurring the growth of the hydrogen energy industry, and facilitating the transformation of hydrogen energy within ship applications. The year 2021 marked a turning point for fuel cell use in ships, catalyzing a surge in development activities within the field. Numerous fuel cell and ship companies have embarked on the journey of developing hydrogen-powered vessels.

China Classification Society (CCS) granted the first maritime fuel cell certification to Wuhan Zhongyu Power Systems Technology Co., Ltd. in early 2021. This milestone not only bridges a gap in China's capabilities but also propels the commercial adoption of hydrogen fuel cell ships. While China is yet to witness fully mature commercial hydrogen energy vessels, CCS remains proactive in its endeavors to drive cost reduction and integrate the entire technological chain, facilitating the establishment of a comprehensive industrial ecosystem centered around hydrogen fuel cell vessels.

In Japan, Kawasaki Heavy Industries, Yanmar Powertech, and Japan Engine Company (J-Eng) jointly announced the creation of HyEng Corporation in August 2021. This collaborative venture is dedicated to developing hydrogen-fueled engines tailored for the maritime industry.

In August 2021, Maersk Group, the world's largest container shipping company, made a groundbreaking move by placing an order for a fleet of massive carbon-neutral ships. These ships will be equipped with hybrid technology, capable of running on conventional low-sulfur marine fuel and carbon-neutral green methanol. This transformative initiative sets a new benchmark for decarbonization and emissions reduction within the container shipping sector, with Maersk investing $1.4 billion in this endeavor.

Noteworthy among these developments is the introduction of the Sea Change, an aluminum catamaran passenger ferry powered entirely by three hydrogen fuel cells driving two propellers. Already launched in July 2022 [107], this commercial ferry, designed by Switch Maritime, will be the world's first of its kind. It will transport 75 passengers along San Francisco's waterfront, representing a pioneering step towards hydrogen-powered maritime transportation.

The shipping industry's transformation towards low-carbon and environmentally friendly operations is both crucial and challenging. With factors like a specific target audience, recent economic downturns, diminishing net profits, and the need for new fuels, encompassing technological, cost, and safety considerations, the transition comes with substantial costs. To achieve a greener future for the shipping industry, the promotion and enforcement of regulations and the proactive involvement of major shipping companies are imperative to lead the way.

4. Problems and challenges facing the development of global hydrogen energy vessels

4.1. Hydrogen sources are not eco-friendly

Currently, the majority of hydrogen production is dominated by gray and blue hydrogen, constituting more than 90 % of the total output. In contrast, the availability of green hydrogen remains limited. Over the past few years, a method known as "high carbonization" has been prevalent in hydrogen production. In the global effort to combat climate change, the strategy is two-fold: "mitigation and adaptation." Achieving "zero emissions" is a collaborative endeavor that no single nation can undertake independently. Consequently, the pragmatic approach has been a blend of primarily gray hydrogen supplemented by blue hydrogen. This approach strikes a

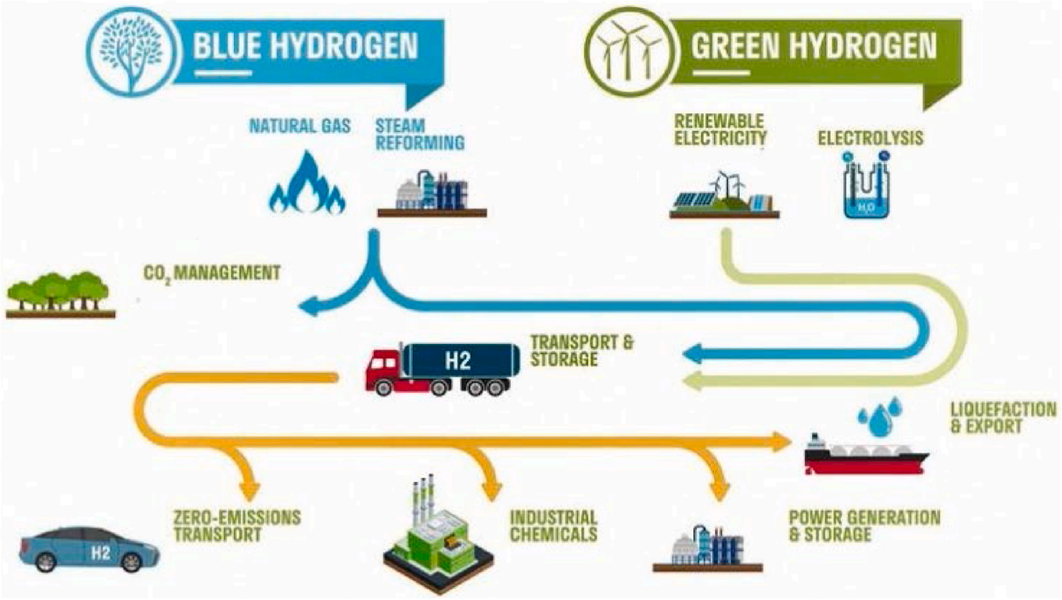

Fig. 6. The process from blue and green hydrogen production to end-use [108]

balance between survival and development imperatives. While green hydrogen is a pivotal solution for a sustainable future, its prevalence remains insufficient. Current manufacturing processes involving electrolysis and thermal energy undermine the environmental significance of hydrogen energy. Instead of producing hydrogen with the intent of fostering clean and efficient sustainability, the focus shifts towards simply using hydrogen as an alternative fuel. Hydrogen production and utilization can be categorized into four overarching groups: traditional methods for conventional applications (such as industrial utilization of gray and blue hydrogen), traditional methods for emerging applications (e.g., fuel cell cars), innovative methods for novel applications, and innovative methods for both new and existing applications. The trajectory of green hydrogen's development will hinge on a delicate equilibrium. As long as the demand for existing applications—both conventional and cutting-edge—is met by the production of gray and blue hydrogen, the evolution of green hydrogen will likely be gradual. Only when market demands display elasticity and adaptability will the proportion of green hydrogen gain prominence. In essence, while the potential of green hydrogen is substantial, its realization depends on a dynamic interplay between production methods, market demand, and sustainable development goals. As nations and industries strive to strike a balance between environmental stewardship and practical needs, the gradual integration of green hydrogen will play a crucial role in reshaping our energy landscape. Fig. 6 shows that Route of hydrogen production (via different energy sources) to end-use.

4.2. The economy needs to be improved

Currently, the cost disparity between green and gray hydrogen is significant, with green hydrogen being approximately three times more expensive to produce. Moreover, the storage and transportation of hydrogen entail higher technical requirements compared to fossil fuels, lacking a cost advantage. Hydrogen refueling stations continue to grapple with the challenge of "hydrogen refueling anxiety," which, although being gradually mitigated, remains a genuine concern. The comprehensive cost structure for hydrogen supply is multifaceted. Even if hydrogen generation costs were low, the cumulative expenses associated with storage, transportation, and recharging would keep end-use application costs high. This economic reality persists across gray, blue, and green hydrogen variants. When factoring in the total equation of "hydrogen production + storage + transportation + hydrogen refueling + carbon," hydrogen struggles to compete with fossil fuels in the market. The journey towards hydrogen industry expansion faces complexities. Relying solely on subsidies is not a sustainable pathway to achieve industrial leaps, and the absence of a hydrogen price advantage hampers the establishment of commercial viability at a large scale. The insufficient scale of the hydrogen ship industry further compounds these challenges. Realizing both industrialization and technical application is imperative for hydrogen to attain competitiveness in its primary markets. Indeed, the promise of hydrogen energy can only be fully harnessed when both industrialization and technical application reach fruition. The progress of hydrogen energy resembles the surging of waves. It is only when both industrialization and widespread technical integration take place that can be harnessed for a comprehensive and influential energy transformation. The prerequisite for this transformation lies in the realization of industrial scale, the development of cost-effective technologies, and the establishment of a competitive landscape, ultimately positioning hydrogen as a compelling alternative in its key markets.

4.3. Technical challenges

The application technology and foundational research capacity of hydrogen energy remain at a moderately developed stage, particularly in nations with significant energy consumption like China and India. While progress is being made, there is a notable lag in the construction of standardization efforts. Specifically, the standardization of hydrogen energy ships is not keeping pace with the requirements of large-scale industrial development. The absence of a globally integrated fundamental standard system could impede the development of new products, markets, and applications for hydrogen energy ships. The hydrogen energy ship sector is characterized by advanced technology, significant demands, high costs, and ambitious goals. This landscape necessitates rapid innovation, development, adaptation, and continuous updates. In order to ensure that the industry progresses effectively, the standard system must evolve in tandem with industrial needs. Striking a balance between technical route alignment and minimizing duplication of efforts is pivotal. Additionally, aligning the absolute and relative strengths of each nation is crucial for a coordinated global effort. In this new era, the development of the hydrogen ship industry's standard system must reach unprecedented heights. Key technological challenges in the hydrogen energy industry include carbon capture, fuel cell optimization, and hydrogen storage safety. Overcoming, enhancing, optimizing, and upgrading these fundamental aspects are critical to transition technologies from mere usability to practicality. For example, in the context of fuel cell systems, catalysts and proton exchange membranes are pivotal components. However, the mass production of platinum alloy catalysts remains limited to only a few companies. These catalysts are both expensive and possess limited reserves of platinum, acting as a significant barrier to the widespread commercialization of fuel cells. Consequently, the creation of cost-effective, efficient low-platinum or non-platinum catalysts becomes imperative to advance the commercial viability of fuel cell technology. In summary, the challenges and opportunities within the hydrogen ship industry underscore the need for a synchronized global standardization system, continuous technological advancements, and collaborative efforts to surmount barriers hindering the practical realization of hydrogen energy's potential.

5. Suggestions for the development of hydrogen ships

The following suggestions are offered for the development of hydrogen-powered ships in order to address the issues that need to be resolved.

5.1 To establish a comprehensive system of hydrogen-powered ship standards and norms, a strategic approach involving a compliance analysis of international technical standards and norms is essential. This process should be underpinned by a thorough examination of the unique application characteristics of hydrogen-powered ship power systems and fuel supply systems. Given the challenging maritime environment characterized by high salt content, corrosion, humidity, vibrations, and impacts, these factors must be carefully considered. A holistic perspective is crucial, encompassing not only successful operations but also potential failure scenarios. Key areas of focus include the selection and arrangement of hydrogen storage equipment, the integration of the hydrogen-powered system with the ship's power supply, strategies to prevent hydrogen leakage, measures for fire extinguishing, ventilation systems, exhaust gas emission protocols, gas and fire detection mechanisms, and comprehensive monitoring procedures. In this endeavor, it is valuable to draw insights from mature land-based hydrogen-powered systems' relevant standard specifications. By adapting pertinent standards to the maritime context, an effective framework for hydrogen-powered ship operations can be crafted. Ultimately, the goal is to formulate a cohesive set of standards and norms that address the unique challenges posed by the maritime environment and the intricacies of hydrogen-powered ship systems. This endeavor requires interdisciplinary collaboration, technical expertise, and a deep understanding of both maritime operations and hydrogen technologies. By aligning these elements and leveraging existing standards where appropriate, a robust and reliable framework for hydrogen-powered ship operations can be established. This system will not only enhance safety and efficiency but also drive the advancement of sustainable and innovative maritime transportation solutions.

5.2 Governments play a vital role in advancing hydrogen fuel cell technology for marine applications. Increasing funding for fundamental research, application demonstrations, and the promotion of critical hydrogen fuel cell components is essential to drive progress. National governments can provide guidance and support to establish a diverse investment ecosystem, with enterprises as the primary contributors, expediting the commercialization of key hydrogen fuel cell components' research outcomes. To effectively cater to the requirements of hydrogen fuel cells in maritime contexts, research should encompass the environmental adaptability of these cells in various conditions. This includes wet and hot environments, salt fog exposure, and conditions involving tilting and swaying. The design of fuel cells must address challenges such as salt fog-induced corrosion, leakage prevention, resilience to ship movements, and resistance to vibrations. Achieving optimal operation of ship fuel cells and ensuring system energy efficiency necessitates an examination of the compatibility between the hydrogen fuel cell system's hardware and the ship's energy management system and strategy. This alignment ensures seamless integration, enabling the system to operate at peak efficiency. Given the intricate structure of hydrogen fuel cell systems and the paramount importance of safety, research and development efforts should focus on creating an online condition monitoring and intelligent fault diagnosis system that harmonizes with the fuel cell system. This advanced system would facilitate real-time monitoring of critical parameters and offer swift identification, location, and isolation of faults, enhancing operational reliability and safety. The collaboration between governments, research institutions, and industry stakeholders is essential to achieve these objectives. By fostering an environment of innovation, collaboration, and knowledge-sharing, governments can facilitate the rapid progress of hydrogen fuel cell technology in the maritime sector, resulting in safer, more efficient, and environmentally friendly marine transportation solutions.

5.3 Advance the field by furthering the development of electro-catalysts, membrane electrodes, and bipolar plates, positioning them as integral components within electrolytic water hydrogen production systems. Central to this advancement is the objective of achieving a twofold impact: the reduction and regulation of costs associated with these systems while simultaneously elevating the efficacy of hydrogen production via the augmentation of catalyst activity. Crucially, the pursuit of cost-effectiveness must remain at the forefront of technological progress. This entails a dedicated effort to refine the underlying technologies, thereby enabling the realization of more economically viable electrolytic water hydrogen production systems. Concomitantly, a paramount goal is to amplify the potency of catalysts operating within these systems. Intensive research and innovation should be geared towards optimizing catalyst performance, thereby translating to enhanced rates of hydrogen production. Moreover, an imperative shift towards a paradigm of multi-energy complementarity is advocated in order to fully exploit the advantages inherent in synergizing various energy sources. This entails the design and implementation of hydrogen production technologies that seamlessly integrate with diverse renewable energy sources. By transcending the limitations of single-energy source hydrogen production, this approach stands to amplify the sustainability and resilience of hydrogen production systems. This pursuit, underpinned by the convergence of cutting-edge electro-catalyst and energy integration technologies, holds the potential to revolutionize hydrogen production by simultaneously advancing efficiency, cost-effectiveness, and environmental sustainability through the strategic fusion of diverse energy inputs.

5.4 Continuing the exploration of hydrogen storage mechanisms remains a pivotal avenue of research. It is imperative to not only investigate theoretical avenues for augmenting hydrogen storage density but also to delve into strategies that facilitate easier hydrogen release. Moreover, there is a pressing need to conceive innovative storage tank designs that embody traits of lightweight construction, robust pressure resistance, and elevated hydrogen storage density. Elevating the production efficiency of high-pressure hydrogen storage tanks necessitates multifaceted approaches, including stringent control over the impurity concentration within raw materials. This control serves to enhance the storage tanks' inherent resistance to the phenomenon of hydrogen embrittlement. The imperative to tailor hydrogen refueling systems to the idiosyncratic operational requisites of maritime vessels cannot be understated. Rigorous design efforts should be channeled towards creating systems that seamlessly integrate with ship operations. Additionally, a systematic investigation into the reliability and robustness of hydrogen refueling strategies across diverse environmental scenarios, ship operational parameters, and varying operational conditions should be undertaken. This scrutiny can be carried out through a combination of simulation studies and experimental testing. Undertaking a comprehensive analysis of the merits associated with different hydrogen storage technologies holds great potential. Particularly, there is a drive to advance composite hydrogen storage technology, which emerges as a promising avenue. In parallel, conducting thorough research to ascertain the feasibility of applying alternative hydrogen storage technologies to maritime vessels, such as low-temperature liquid hydrogen storage and organic liquid hydrogen storage technology, is of paramount importance. These technologies warrant meticulous examination in the context of their compatibility with ship-based applications.

5.5 Broaden the scope of research pertaining to hydrogen leaks, hydrogen combustion, and explosion mechanisms, with a specific focus on elucidating the transition process from a hydrogen explosion to a detonation. Enhancing the precision and reliability of the numerical simulation model necessitates the compilation of historical data related to hydrogen leakage and diffusion. Alternatively, conducting leakage and diffusion experiments using helium, leveraging its analogous diffusion properties to that of hydrogen, and subsequently refining the numerical model through the assimilation of these test outcomes is recommended. Offering robust technical remedies and methodologies, such as forced ventilation, real-time monitoring, and emergency shutdown protocols, emerges as essential approaches capable of mitigating or minimizing the safety hazards posed by accidents. These recommendations stem from the simulation-derived insights gleaned from incidents involving hydrogen leakage, diffusion, combustion, and explosions on maritime vessels. In order to delineate the perimeters of risk inherent to the operation of hydrogen-powered ships and to delineate the zones of risk influence along their routes, the establishment of a comprehensive safety risk assessment model tailored specifically for hydrogen fuel cell-driven ship navigation becomes imperative. This model should take into meticulous account a gamut of factors, including meteorological conditions impacting ship navigation, hydrological conditions, proximity to waterways, the presence of marine infrastructure, intersections with other vessels, and various other relevant variables.

6. Conclusion

In summary, a pressing imperative exists to propel the domains of safe hydrogen production, secure hydrogen storage, optimized hydrogen power units, and the commercialization of hydrogen-powered ships to the forefront of hydrogen energy maritime advancement. This pursuit demands the swift development of hydrogen storage technologies and potent hydrogen power plants that amalgamate considerations of safety, efficiency, and economic viability. Presently, a stark insufficiency in both hydrogen storage safety protocols and hydrogen power plant capabilities underscores the critical nature of our endeavors. Concurrently, an immediate call to bolster national standards governing hydrogen-powered vessels is paramount to ensure uniform safety and operational guidelines across the sector.

Embarking upon the journey of hydrogen-powered ship development necessitates a concerted effort to surmount a multitude of technological and financial obstacles. Key among these challenges are the domains of hydrogen fuel cell technology, hydrogen power plant engineering, the intricacies of hydrogen storage safety, the varied policies enacted by nations with regard to hydrogen-powered ships, the trajectory of technological advancement, and the path to achieving widespread commercialization. In the context of high-pressure gas hydrogen storage and transportation, high-pressure ambient hydrogen storage emerges as the sole commercially viable hydrogen storage technology presenting low operating costs, a straightforward container structure, and facile recyclability. This technology is poised to dominate the hydrogen marine sector over the forthcoming decade due to its inherent advantages. Simultaneously, the emergence of low-temperature compression hydrogen storage introduces a novel paradigm that merges the attributes of high-pressure and low-temperature hydrogen storage, culminating in an impressive storage density of 71.5 kg/m^3. However, it is imperative to acknowledge that the dual requirements of sustaining low temperatures and high pressures engender augmented costs related to preparation and storage vessel construction. Progress within the domain of high-pressure hydrogen storage cylinders gravitates towards lightweight constructions, elevated pressure thresholds, and augmented hydrogen storage densities. Evidenced by the advent of innovative Type V cylinders, this sector is swiftly evolving. Employing individual strategies such as moderating ambient or hydrogen inlet temperatures, curbing filling rates for extended filling durations, or adopting staged filling techniques have proven efficacious in ameliorating high-temperature phenomena and bolstering filling capacities. Nevertheless, a comprehensive exploration of the interplay between multiple influencing factors remains an ongoing area of investigation.

From a comprehensive perspective on the evolution of the hydrogen fuel cell industry, the ascent of fuel cells as a novel, clean energy source initially found its foothold in the automotive sector. The journey began with demonstration operations within the automotive realm, and as the fuel cell industry ecosystem matured and market demands for fuel cells extended to maritime applications, a gradual foundation was laid for integrating hydrogen fuel cell power systems into ships. However, a notable distinction surfaces between marine fuel cells and their automotive counterparts across dimensions such as power requisites, design criteria, safety mandates, and operating environments. These disparities necessitate the concerted efforts of research and development entities and experts to not only refine specifications and standards tailored to marine fuel cells but also to complement and optimize the existing technological framework. Undoubtedly, the trajectory of hydrogen energy points towards the eventual displacement of conventional fossil fuels, culminating in its widespread integration across a diverse range of ship types and domains. As a transformative force, hydrogen-powered ships are destined to be pivotal players in the realm of green shipping, ushering in an era characterized by cleaner and more sustainable maritime operations. This transition promises a dual impact, enhancing both the efficiency and stability of shipping operations while concurrently mitigating the emission of pollutants originating from ships. Looking ahead, the shipping sector is poised to embrace a myriad of opportunities and challenges as hydrogen-powered vessels evolve into the standard propulsion method. This progression stands as a testament to technological advancement and portends a future where hydrogen ships not only contribute to the reduction of environmental impact but also drive forward the frontiers of maritime innovation.

This article provides a summary of the development of hydrogen fuel cells, hydrogen storage technology, and the current status of hydrogen-powered vessels. However, there are still many shortcomings. The impact of hydrogen storage tanks on ship safety during navigation, hydrogen refueling for maritime applications, and the selection of materials for shipboard hydrogen storage tanks are areas that require further consideration. In the future, it is important to optimize shipboard hydrogen storage tanks and their securing mechanisms in response to real-life conditions encountered during ship operations, ultimately enhancing the safety of shipboard hydrogen storage tanks.

Data availability Statement

Data availability is not applicable to this article as no new data were created or analyzed in this study.

CRediT authorship contribution statement

Ji-Chao Li: Writing – original draft, Resources, Formal analysis, Data curation. **Heng Xu:** Visualization, Validation, Supervision, Software, Resources, Investigation, Formal analysis, Conceptualization. **Ke Zhou:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Ji-Qiang Li:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have on known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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