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Decarbonization of shipping: Hydrogen and fuel cells legislation in the maritime industry

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ABSTRACT

The maritime industry is a significant component of the transportation sector. Ships are the major element of the maritime industry, and propulsion power comes from fossil fuels, such as heavy fuel oil or marine diesel oil. These fossil fuels are used in conventional marine diesel engines and result in high levels of harmful emissions. These emissions contribute to the greenhouse effect and global warming, which is why efforts have been made to regulate and limit them within specific boundaries through various rules and regulations. However, with current technology, it is not possible to stay within these regulations. Therefore, the maritime sector has embarked on the quest for alternative power sources, and as a result, alternative fuels and fuel cells have gained importance. Hydrogen, one of these alternative fuels, is a promising solution with a carbon-free structure for the maritime industry to move toward sustainability. However, ships are considered high-risk areas, which is why specific standards need to be established for the use of hydrogen and fuel cell technology in ships. Hydrogen bunkering, onboard storage, and power system design, limits, and operational aspects must be properly elaborated. Although there are several substantial international standards and regulations for gas, liquid, and dangerous cargo, there is a lack of specific and detailed regulations for the use of fuel cells and hydrogen fuel onboard ships. This paper reviews the relevant regulations and standards while showing the regulatory gap concerning hydrogen and fuel cells by discussing the main barriers and highlights the current and future agenda of the industry toward decarbonization vision.

1. Introduction

The shipping industry plays a key role in global trade, accounting for over 80% of total trade [1]. For over a century, marine diesel engines have been the primary propulsion systems for ships. As the industry grapples with environmental concerns, there is growing interest in shifting away from fossil fuels, such as marine diesel oil (MDO) and heavy fuel oil (HFO), to generate the required propulsion power from cleaner sources. The predominant use of fossil fuels in the past has been driven by their major advantages, which include ease of handling, cost-effectiveness, and reliability [2]. However, the use of fossil fuels has significant

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disadvantages in terms of environmental effects. The maritime transport sector accounts for approximately 3% of worldwide anthropogenic greenhouse gas (GHG) emissions, and projections indicate that CO_2 emissions in the maritime sector are expected to increase by 50% from 2008 to 2050 [3]. In the revised strategy for 2023, these objectives have been significantly sharpened. Within this updated framework, there is an expectation that the total annual GHG emissions will decrease by 30% by 2030 and by 80% by 2040, ultimately aiming to achieve net-zero emissions by 2050 [3]. To understand the emission potential of this industry, it can be said that the amount of greenhouse gas (GHG) emissions from international maritime transportation is comparable to the GHG emissions of Germany [4]. Maritime transportation GHG emissions, CO_2, methane (CH_4), particulate matter (PM), sulfur oxides (SO_x), and nitrous oxides (N_2O) have increased from 977 million tons to 1,076 million tons, and CO_2 emissions have increased from 962 million tons to 1,056 million tons from 2012 to 2018 [5]. CO_2 emissions constitute the majority of greenhouse gas (GHG) emissions from maritime transportation. The International Maritime Organization (IMO), the ruler of industry, is continuously implementing regulations and standards for environmental protection in the global shipping industry. The main motivation of the IMO is to minimize ship-sourced greenhouse gas (GHG) emissions by forcing the industry to meet emission limitation regulations [3]. International Convention for the Prevention of Pollution from Ships (MARPOL), Annex VI Regulations for the Prevention of Air Pollution from Ships is the main strategy for controlling ship-sourced emissions in global shipping [6-7].

On the other hand, the IMO not only establishes regulations but also introduces key measures to achieve the emission reduction and zero-carbon goal of the global maritime industry. The Energy Efficiency Design Index (EEDI), Ship Energy Efficiency Management Plan (SEEMP), Energy Efficiency Existing Ship Index (EEXI), and Carbon Intensity Index (CII) are measures that limit emissions from ships [8]. The EEDI, introduced in 2011, sets a CO_2 limit per ship capacity mile for ships above 400 gross tons [9]. Subsequently, the SEEMP was introduced as an operational measurement tool for ships. However, it is important to note that the SEEMP itself is not a direct measure; instead, it offers an approach for monitoring the energy efficiency of ships and fleets. This plan serves as a valuable tool for enhancing energy efficiency and consequently reducing emissions. However, these actions were not sufficient for the ultimate target of the IMO, and two new measures (EEXI and CII) were introduced to reduce emissions. In November 2020, EEXI and CII were announced to have entered into force by January 2023 [10]. EEXI is applied to all merchant ships over 400 gross tons [11]. The idea is similar to the EEDI in reducing the CO_2 emissions of ships per nautical mile. EEXI is again ship-specific and different for all types and powers of the ships. Lastly, CII was entered into force in January 2023, and it is applied to ships over 5000 gross tons [12]. The annual CO_2 emissions from ships were assessed and categorized on a scale ranging from A to E [13]. “E” represents the lowest level of emissions, and if a ship reaches this rating, its International Air Pollution Prevention (IAPP) certificate is temporarily suspended, and it is prohibited from sailing until appropriate corrective measures are implemented. Furthermore, the IAPP certificate is suspended in the same manner if a grade of D is attained on three consecutive occasions.

To reach the 2050 goal, there are different approaches in industry and academia, and they can be mainly grouped by changing the fuel, propulsion technology, and exhaust treatment technologies [14–16]. The industry primarily focuses on the adoption of emission abatement technologies and exploration of alternative marine fuels [17]. Alternative fuels considered for maritime transportation include ammonia, biodiesel, dimethyl ether (DME), ethanol, hydrogen, methanol, liquefied biogas (LBG), LNG, and liquefied petroleum gas (LPG) [18–21]. While these low-carbon alternatives play a significant role in reducing GHG and CO_2 emissions, it is imperative to recognize that zero-carbon alternative fuels will be necessary to achieve the IMO Strategy 2050 emissions target. Consequently, hydrogen can be considered a zero-carbon alternative fuel for maritime use in the long term [22]. Emission limitations have set the stage for hydrogen and play a key role in the transition to zero-emission shipping with its carbon-free structure. Consequently, hydrogen storage, bunkering, and powering with fuel cells have become increasingly significant, particularly in the transportation sector, which is actively striving to decrease its reliance on fossil fuels. Hydrogen exists in a gaseous state and is the most abundant element in the universe. Compared to other fuels, hydrogen possesses the highest energy content per unit weight [23]. However, because of its gaseous nature at room temperature, hydrogen must be stored either as a compressed gas at 300 bar and 25°C or as a cryogenic liquid at 1 bar and

-253°C. Hydrogen storage is an energy-intensive process, resulting in elevated storage costs, and has not been experienced in maritime conditions. Additionally, various stages of the hydrogen storage chain exist within vehicles, refuelling stations, and the broader context of hydrogen production and distribution [24]. Research on hydrogen storage within the transportation sector has predominantly focused on fuel cell electric vehicles (FCEVs) [25]. Fuel cells are electrochemical devices that convert the stored chemical energy in hydrogen to electrical energy without any combustion process [26]. Fuel cells use hydrogen as fuel but some types can also operate with hydrocarbons such as LNG or diesel oil thanks to the reforming process. The most common approach to the classification of fuel cells is by the type of electrolyte used. There are six commercial types of fuel cells: Proton Exchange Membrane Fuel Cell (PEMFC), Solid Oxide Fuel Cell (SOFC), Molten Carbonate Fuel Cell (MCFC), Phosphoric Acid Fuel Cell (PAFC), Alkaline Fuel Cell (AFC), Direct Methanol Fuel Cell (DMFC). Among the various types of fuel cells, proton exchange membrane (PEM) fuel cells have led to technological maturity. In the literature, SOFC and MCFC are also classified as high-temperature fuel cells, since their operation temperatures are around 800-1000 °C and 650 °C, respectively [27]. Owing to their power generation way, fuel cells can reach higher efficiencies compared to internal combustion engines, especially diesel engines regarding to maritime industry. For instance, the SOFC can achieve efficiencies up to 60% solely [28], while the PEMFC is above 50%. Furthermore, the high-temperature types can be hybridized with gas turbines to achieve much higher efficiencies instead of stand-alone configurations. Although fuel cells seem advantageous from many perspectives, the capital cost and onboard storage of the hydrogen are the major obstacles in front of this alternative technology [29-31]. Numerous projects involving the utilization of hydrogen and fuel cells on ships have been initiated and are currently ongoing [27].

Hydrogen and fuel cells, viewed as solutions to the emissions problem in the maritime sector, should be subject to the creation of new rules and regulations for their adaptation in the maritime industry. Although several approaches have been implemented by the IMO and classification societies, there is still a gap in guidelines and regulations, especially for hydrogen storage, bunkering, and fuel cell systems. This paper aims to examine the current rules and regulations related to hydrogen and fuel cells in maritime areas, while also seeking to draw lessons that can be learned from the transportation sector. It particularly focuses on evaluating the main barriers to system adaptation and looks for insights that may help the maritime sector achieve its ultimate goal of achieving carbon neutrality. The remainder of this paper is organized as follows: Section 2 reviews the international rules and regulations related to hydrogen and fuel cells, Section 3 reveals the main barriers to hydrogen and fuel cell adoption to merchant ships, Section 4 discusses the regulatory gaps, details the current and future agenda of the industry, and finally, Section 5 concludes the paper.

2. Hydrogen and Fuel Cell Related International Legislation

In the maritime industry, although there are numerous codes, regulations, and standards that can be associated with fuel cells and hydrogen fuel, their effectiveness remains limited. Safety concerns related to alternative fuels, including hydrogen, have been addressed in the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code), and the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). On the operational and equipment sides, the International Convention for the Safety of Life at Sea (SOLAS) has emerged as a fundamental framework, even though it does not directly focus on fuel cell systems or hydrogen fuel.

The International Maritime Organization (IMO) issued interim guidelines for the installation of fuel cells on board ships. In addition, classification societies have developed various rules and guidelines for the installation of fuel cell systems and their components in maritime applications. A summary of related legislation is presented in Figure 1. The main goal of the introduced codes and standards is to assist the hydrogen-powered vessels. Class societies or Flag States may add additional requirements to ships under their control.

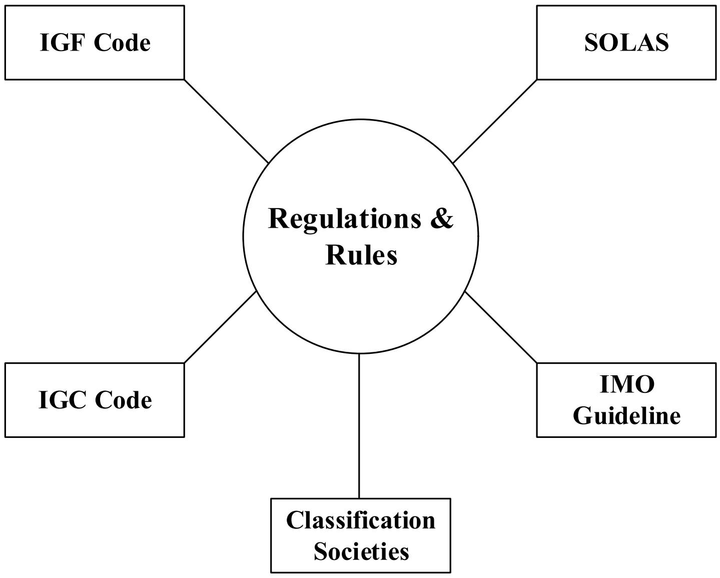

Fig. 1 Hydrogen and fuel cell-related international legislation

2.1 IGF and IGC Codes

The International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) was adopted in 2015 and entered into force on January 1, 2017, providing safety guidelines for the use of low-flashpoint fuels [32]. The goal of this code is to establish a global standard for ships powered by gas fuels or low-flash-point liquids. Using this code, several amendments have been added to Chapters II-1 and II-2 of the International Convention for the Safety of Life at Sea (SOLAS) [23]. The code sets mandatory guidelines for the installation and utilization of design, construction, equipment, and operational procedures. Its fundamental principle is to minimize risks to ships, their crews, and the environment. The IGF Code covers all aspects that require special scrutiny concerning the use of gases or low-flashpoint liquids as marine fuels, as outlined in the MSC 1/Circ. 1394. Consequently, it defines the objectives and operational requirements pertaining to design, structure, and operation, each of which is covered within distinct chapters. It mainly focuses on the use of liquefied natural gas (LNG) in ships. However, it is designed to evolve continuously, with future updates expected to incorporate requirements for other types of low-flashpoint fuels [24]. The IGF Code also includes provisions for the use of hydrogen fuel cells in ships within a limited frame. Second, The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) sets out requirements for the design and construction of ships carrying liquefied gases, including hydrogen. The IGC Code plays a crucial role in ensuring the safe transport of liquefied gases by sea and addressing the unique safety challenges posed by these cargoes (International Maritime Organization [25]. It contributes to the protection of human lives, the environment, and property by establishing strict safety measures and guidelines for gas carriers and their operation.

2.2 SOLAS

The International Convention for the Safety of Life at Sea (SOLAS-1974) defines safety standards for ships, including the requirements for their construction, equipment, and operation. SOLAS does not directly address fuel cells for ships, but provides general safety requirements. These requirements cover topics such as fire safety, electrical safety, and prevention of explosions and leaks. It continues to evolve to address new developments in the shipping industry as additional amendments and codes, such as the IGF. Therefore, fuel cell systems and equipment should comply with SOLAS standards to be mounted on ships.

2.3 IMO Fuel Cell Guideline

The interim guidelines for the safety of ships using fuel cell power installations have been approved by the IMO Maritime Safety Committee (MSC.1/Circ. 1647) in June 2022. The guideline is the most detailed and up-to-date document on the installation of fuel cells in ships. The guidelines provide criteria for the arrangement and installation of fuel cells onboard ships to provide at least the same level of safety as new and comparable conventional oil-fueled main and auxiliary engines [26]. The most detailed international paper is this guideline for fuel cells; however, a specific guideline for hydrogen is still lacking. The document is closely linked to the IGF Code, which considers hydrogen as the primary fuel type of fuel cell. The guidelines are formed from five sections: functional requirements, design principles, fire safety, electrical systems, and control, monitoring, and safety systems. The functional requirements are almost equal to those of the IGF Code, and additional requirements should be met according to the fuel cell and hydrogen systems. In addition, these guidelines provide important design principles for fuel cell installation onboard ships. The sub-categories of the design principles are as follows: fuel cell spaces, arrangement and access, atmospheric control of fuel cell spaces, materials, piping arrangement of fuel cell power system, exhaust gas, and exhaust air. The fire safety section provides information regarding design and fire mitigation strategies. The electrical systems section includes the design, hazardous-area classifications, and risk analysis. The last section focuses on gas vapor detection, ventilation, emergency shutdown, fire detection, and alarm actions. The published guidelines are substantial and provide a cornerstone for fuel cell installations on board ships.

2.4 Classification Societies

Classification societies are non-governmental organizations that establish technical standards for the design, construction, and operation of ships. Several classification societies such as DNVGL, Lloyd's Register (LR), American Bureau of Shipping, Bureau Veritas (BV), Turkish Lloyd (TL), and Korean Register (KR) have introduced fuel cell installation, hydrogen fuel handling, and safety guidelines. The guidelines cover information about safety, electrical systems, implementation, ventilation, and system controls. Table 1 shows the developed rules by the class societies.

Table 1 Technical standards of hydrogen fuel cells for ships by classification societies

Classification Society	Related Document	Year
DNVGL	Handbook for Hydrogen-Fueled Vessels	2021
	DNV GL rules for classification of Ships: Part 6 Ch. 2 Sec. 3: Fuel cell installation - FC	2016
KR	Guidance for Fuel Cell Systems on Board of Ships (updated)	2022
	Guidance for Fuel Cell Systems on Board of Ships	2014
ABS	Requirements for Fuel Cell Power Systems for Marine and Offshore Applications	2023
LR	Guidance Notes on the Installation of Fuel Cells on Ships	2022
	Development of requirements for Fuel cells in the marine environment – Performance and prescription	2006
TL	Rules on the Use of Fuel Cell Systems on Board Ships	2005
BV	Guidelines for the Safe Application of Fuel Cell Systems on Ships	2022
	Guidelines for Fuel Cell Systems Onboard Commercial Ships	2009

3. Main Barriers to the Hydrogen and Fuel Cell Establishment

While fuel cells and hydrogen are promising alternatives for the maritime industry, they have not yet gained widespread adoption in today's global maritime industry. There are a variety of multiple barriers contributing to this situation. The main barriers that require to be highlighted are given in the Figure 2 below:

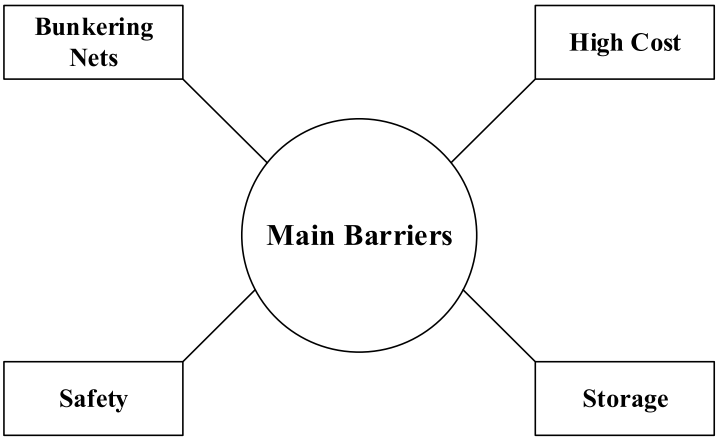

Fig. 2 Main Barriers to the establishment

- Bunkering Nets: One of the biggest obstacles to the widespread use of hydrogen in shipping is the lack of global hydrogen bunkering nets. When considering a worldwide perspective, it is essential to establish large-scale hydrogen bunkering stations on the most active trade routes where the emission impact is most significant in the initial phase. European, Asian, and American coasts have the major priority considering the trade volume, ship traffic, and human population. On the other hand, production of the hydrogen and supplying it to the bunker port remain a challenge. Safe and efficient hydrogen bunkering operation from land to ship requires a detailed design and construction of new infrastructure [27]. At present, there is an inadequacy in infrastructure for producing, transporting, storing, and providing bunkering services for hydrogen. Without regulatory intervention, the substantial investments needed would result in elevated fuel costs. Nonetheless, due to the progressively stricter regulations concerning local emissions within Emission Control Areas (ECAs) and nearby port areas, the necessity for eco-friendly fuel infrastructure is steadily growing.
- High Cost: The transition and application of a new technology especially considering a new fuel is directly related to higher costs for the maritime industry. Hydrogen and fuel cells have higher capital and operational expenditures compared to fossil fuels and marine diesel engines. The unit price of fuel cell stacks is more than 50 $/kW for PEMFC [28] which is significantly more expensive than the conventional marine diesel engines. Furthermore, the higher cost of auxiliary systems like power electronics, monitoring systems, and fuel conditioning units is more expensive than the traditional ship power plants [10]. Lifetime is also another important approach to evaluate the cost of the fuel cell system compared to traditional marine power plants. 40,000 h is reached by high-temperature fuel cells [29] but still shorter than the marine diesel engines. On the other hand, operational costs of the fuel cell systems are directly related to fuel cost and fuel consumption, and so system efficiency. The overall efficiency of the fuel cells is higher than the marine diesel engines especially when they are hybridized with gas or power turbine systems to recover waste heat [30-31]. Also, the energy management strategy for the fuel cell systems is crucial for efficiency [32–34]. An operation profile-based design and energy management strategy are crucial for fuel cell ships to reach higher efficiencies for reducing fuel consumption and minimizing operational costs.
- Safety: Safety concerns related to fuel cell ships are mostly focused on hydrogen fuel. Onboard handling, bunkering, and storage of the hydrogen require different additional precautions that the industry experienced. Since hydrogen is highly flammable and volatile, proper handling at high-

pressure or cryogenic tanks with adequate ventilation is substantial. Hydrogen has wide flammability limits (4-75%) in the air which may cause high explosion or fire risk [35]. Furthermore, as mentioned earlier, the lack of infrastructure and experience in the maritime industry creates uncertainty for stakeholders. New and inexperienced technologies also necessitate additional crew education for safe operations.

- Storage: Hydrogen storage is one of the most significant barriers to the use of hydrogen as fuel in ships. There are four primary storage methods available to use in ships: compressed storage, liquid storage, solid-state storage, and alternative carriers, as illustrated in Figure 3 [36–38]. Storing the hydrogen in compressed form is the most well-experienced storage technology compared to others. However, it increases the cost and requires more energy to pressurize the tank, and the tank material becomes more important. The pressure is around 350-700 bar and it is advantageous in gravimetric density [39–40]. Another technique of storing hydrogen is by liquefication process, which involves cooling the fuel to -253 C. The goal is to increase the density rather than the vaporous structure of hydrogen. In this method, heat isolation is crucial to ensure higher efficiency by reducing the evaporation in the storage tank. Solid-state hydrogen storage represents a third method, but it may not be suitable for maritime conditions due to limitations in ship volume, both in terms of gravimetric and volumetric storage capacity. Since the carrying capacity of the ships is limited, it would reduce the space for cargo.

Finally, alternative hydrogen carriers can resolve the storage challenges for ships, with ammonia being a predominant choice among these carriers [41]. Consequently, rather than transporting hydrogen directly, the use of ammonia is a more accessible and cost-effective option owe to its easier physical properties. As a result, all these storage methods are more challenging and expensive compared to storing conventional marine fuels like diesel oil or heavy fuel oil.

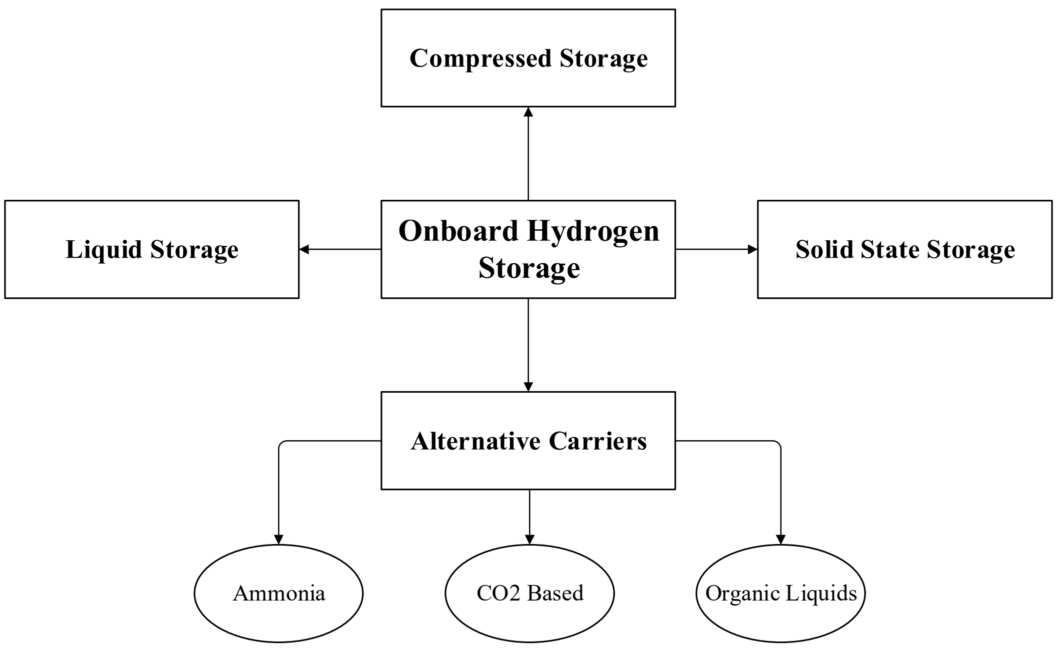

Fig. 3 Onboard hydrogen storage techniques

4. Discussion & Prospects for the Future

The future of fuel cells and hydrogen is promising for the maritime industry and can significantly contribute to achieving zero-emission shipping objectives. However, despite their numerous advantages, there are various barriers to its commercialization at different levels. The major obstacles identified include the high cost of fuel cells compared to diesel engines, safety uncertainties, technological maturity, the global hydrogen bunkering network, and port infrastructures. Additionally, difficulties associated with hydrogen bunkering and the associated high risks represent secondary obstacles, particularly when considering the high level of comfort with traditional fuels and diesel engines. Moreover, organizational and behavioral challenges should not be dismissed, since the resistance to change and a lack of knowledge, when combined with a lack of organizational structure, can become significant barriers [42]. Although marine diesel engines are the major propulsion power source in the maritime industry, incoming emission regulations are limiting the borders of this technology, and forcing the industry to find more environmentally friendly solutions. The most recent emission limitation regulation in this field is the Emission Trading System (ETS), which came into effect on January 1, 2024. Under this rule, ships' carbon dioxide emissions in European ports will be calculated annually and taxed. The funds generated from this tax will be used in the research and development of more environmentally friendly fuel and power technologies. Currently used ship diesel engines using fuel oil and diesel oil result in approximately 3.2 times more carbon dioxide emissions per unit of fuel burned [21]. Consequently, ships operating in the European region are now subject to an additional cost. Therefore, in the coming years, starting from European ports and extending globally, the use of environmentally friendly fuels and/or power generators will become imperative in maritime transportation [43].

High comparative costs pose a significant challenge when transitioning from fossil fuels to hydrogen, and from conventional diesel engines to fuel cells. Three key approaches can be followed to address this challenge; increasing fines or taxes for ship-sourced emissions, increasing the cost of fossil fuels or decreasing hydrogen and fuel cell costs by increasing the total yearly capacity or using more budget-friendly materials. As a first option, current prices of ships' fossil fuels, HFO, MDO, and LNG need to be increased in favor of hydrogen to be more competitive in the market. The second option could involve raising fossil fuel taxes or emission fines for ships operating within specific sectors like Emission Control Areas (ECAs), European coasts, Nordic Coasts, American Coasts, Mediterranean Sea, Black Sea, and similar regions. Therefore, this would force the ships that work in these areas to switch their fuel type to carbon-free options. Thirdly, much research indicates that increasing the annual production volume of fuel cells would lead to a decrease in the cost per energy amount in kilowatt-hours. For this reason, increasing the production capacity of fuel cells and making hydrogen production more cost-effective will pave the way for the presence of hydrogen and fuel cells in the maritime sector. Simultaneously, through pilot projects in the sector, the acquisition of technical, economic, and operational experience will lead the way in removing barriers to fuel cells and hydrogen fuel by advancing their adoption.

On the other hand, financial support for the maritime sector on both national and international levels regarding hydrogen and fuel cells will change the industry's readiness level towards uncertainties and risks in this field. In this regard, examples can be drawn from the high-budget projects undertaken by the United Nations and the European Commission from the land transportation sector, which encompasses vital components such as automobiles, buses, and heavy freight transport. For instance, The European Commission's objective within the Hydrogen Strategy for Europe frame is to establish uniform standards, terminology, and enhanced certification processes, enhancing the competitiveness and ease of use of renewable or low-carbon hydrogen as an alternative fuel resource [44]. Despite the publication of certain guidelines and regulations by various stakeholders in the maritime sector, there are still regulatory and standardization gaps in the use of hydrogen and fuel cells on ships. This situation arises from a lack of harmonization in the rules and approaches among the infrastructure underpinning international organizations at the global level. Therefore, land-based applications can draw a framework to the maritime owing to the regulatory regime for the required bunkering stations and hydrogen fuel cell ships. Standards from the American Society of Mechanical Engineers (ASME), the Society of Automotive Engineers (SAE), the International Standardization Organization (ISO), and the International Electrotechnical Commission (IEC) are the most used in general. Other standards are used depending on geography; for example, EU directives and standards are used in the EU area. Most-related fuel cell and hydrogen-based standards from other industries are summarized in Table 2 as follows.

Table 2 Fuel cell and hydrogen related standards from other industries

Standard	Content / Scope
ISO TR 15916	Safety-relevant properties for hydrogen.
IEC 62282	A series of standards from part 1 to 7 including; terminology, modules, safety systems, applications, portable systems, micro systems, and test methods.
SAE J2578	Safe design, operation, and maintenance of fuel cell electric vehicles (FCEVs).
SAE J2579	Specifications for the quality of hydrogen fuel to be used in FCVs.
ASME B31.12	Standards for piping.
ISO 14687	Standard specifies the minimum quality requirements for hydrogen fuel used in applications.
ISO 16110	Standard provides guidelines for the safety and performance of hydrogen generators that use fuel processing technologies.
ISO 16111	Standard specifies the requirements for the quality of compressed hydrogen gas used as a fuel.
ISO 16112	Standard specifies the quality requirements for liquefied hydrogen fuel.
ISO 16113	Standard specifies the quality requirements for gaseous hydrogen fuel.
ISO 19880	Safety and performance requirements for PEM fuel cell.
ISO 19881	Standard specifies the requirements for hydrogen using PEM FCVs.

The provided standards in Table 2 can also be considered fundamental references for the maritime sector. It is necessary to subject these standards to various regulations for their implementation on ships. This requirement arises due to ships being considered high-risk areas and operating under challenging open sea conditions. To ensure the safety of ships and environmental compliance, it is important to apply these standards in various areas such as ship design, operation, fuel storage, and usage. In this way, the maritime sector can operate safely and sustainably by conforming to internationally accepted standards. The main regulatory gaps and challenges faced by the maritime industry on the implementation of hydrogen and fuel cells arise from the lack of internationally accepted standards. The maritime sector, in general, follows the automotive sector in terms of technology. Therefore, hydrogen and fuel cell standards based on the automotive industry can be considered the foremost example ahead of the maritime sector. The existing regulations for hydrogen and fuel cells in the maritime sector lack sufficient safety, quality, performance, and minimum requirement standards. The standards defined under the IGF Code primarily focus on liquefied natural gas, and although hydrogen is considered a reference point for fuel cells, its inherent nature necessitates different selection standards. However, due to the absence of a correlation between hydrogen and natural gas among marine diesel engines and fuel cells, entirely innovative and different approaches are required. The current regulations are unable to establish a reference standard for fuel cells and remain at the IMO Guideline level. In this context, considered possible regulations can be categorized under three subtitles; safety, design, and operational and they should provide enough knowledge about these topics. Their contents can be summarized as follows, in Table 3.

Table 3 Possible different levels of the considered fuel cell regulation for ships

Safety	Design	Operational
System Installation	Material and Installation	Periodical Inspections
Room Ventilation	Fuel Cell Unit	System Maintenance
Protective Equipment	Onboard Hydrogen Storage	Fault Diagnostics
Fire & Explosion Protection	Fuel Supply & Bunkering	System Testing
Fire Detection	Fuel Transfer	Commissioning Procedure
Surveillance	Port Facilities	Fuel Bunkering Procedure
Electrical Safety		Energy Management System

Table 4 Comparative table under different aspects

Aspect		Conventional Fuels		Hydrogen and Fuel Cells	
		Pros	Cons	Pros	Cons
Environmental Impact	GHG Emissions & Air Quality	Emission targeting well-established regulations, i.e., MARPOL Annex VI	Limited ability to reduce, high carbon content	Fully elimination of GHG emissions, water vapor only	Challenges in clean hydrogen production
	Oil Spill	Established protocols for oil spill response, i.e., SOPEP, SMPEP	Difficulties in operations	No content of oil	Lack of protocols in case of gas leakage
Safety	Fire & Explosion	Crafted guides for gas and explosive fuels i.e., IGF Code	Flammable fuels	Less flammable	Challenges in safe storage and handling of hydrogen
Economic	Capital Expenditures	Established market	Modification requirements for evolving regulations	The potential of long-term cost savings	High cost for installation
	Operational Expenditures	Relatively stable	Politically affected	Potential stability regarding improvement in hydrogen production technology	Volatile during market initial

Another topic of concern is hydrogen bunkering and storage on ships. The bunkering operation of hydrogen requires coherence between many stakeholders at different levels such as supplier, receiver, port authority, and flag authority. The IGF Code consists of some technical and functional requirements for the receiving ship however, it does not cover the entire bunkering process and its stakeholders. Furthermore, existing regulations, codes, and standards do not address the complexities and safety issues associated with the implementation of new technological solutions required for the rapid bunkering of substantial quantities of hydrogen onto ships. Consequently, there is a need for enhanced knowledge, further technological advancements, and practical testing of the anticipated innovative solutions. Risk-based methodologies are likely to be essential when determining safety distances for hydrogen bunkering. However, the definition of what constitutes an acceptable risk in bunkering operations may vary and will typically be guided by general regulations according to the countries or regions where the ship is intended to operate. In cases where such criteria are absent, insights from experiences in other sectors, especially those gained from the development of land-based hydrogen infrastructure, may prove valuable. In this perspective, Table 4 is formed to reveal the pros and cons of regulations for conventional fuels compared to the fuel cell and hydrogen-based regulations.

5. Conclusion

Fuel cell-powered ships are emerging as a promising environmentally friendly technology in the maritime industry. Numerous theoretical studies and industrial applications have explored their system availability and efficiency. However, for these technologies to become commercially viable and widely adopted in the maritime sector, it is essential to establish comprehensive and well-defined regulations at the international level. Despite the significant potential in this field, there is currently a regulatory gap. Fuel cells are already making their way into commercial use in maritime applications. Therefore, it is crucial to actively develop and enhance both national and international regulations and technical standards related to fuel cells and hydrogen. This should encompass considerations of potential hazards, risks, operational aspects, and implementation techniques. With the aim of establishing a reference point within the maritime industry, this paper delves into hydrogen and fuel cell-based regulations, drawing insights from other industries. Previous sections provide a summary of regulations pertinent to gas and alternative fuels in relation to ships, highlighting their shortcomings. The proposed regulation framework is categorized into three sections: safety, design, and operational. These sections derive their content while preserving the essence of analogous regulations in industries such as automotive, stationary applications, and aviation. Key standards, such as those established by ISO, SAE, and ASME, serve as crucial reference points for the newly formulated hydrogen and fuel cell regulations tailored for the maritime sector. Within this context, the paper expounds on the pros and cons of both conventional fuel and hydrogen fuel cell-based regulations, focusing on environmental impact, safety considerations, and economic aspects.

To promote the broader adoption of hydrogen and fuel cells in the maritime industry, the implementation of well-coordinated regional and international policies is imperative. It is equally important to align policies between the energy and shipping sectors. Prioritizing hydrogen-based fuels as a leading energy source can make a substantial contribution to the decarbonization of ships. Policy interventions will be essential to facilitate the uptake of hydrogen and overcome the barriers associated with their use, including high costs, supply limitations, infrastructure constraints, and the uncertainties and risks faced by early adopters.

Addressing these barriers will require close coordination and collaboration among national and international authorities and maritime stakeholders. An initial step could involve the formation of working groups tasked with defining a clear strategy and specific objectives. Policymakers will need to assess the cost-effective potential of each fuel for various routes, both national and international, and determine the most effective methods for introducing these fuels. They must also identify when subsidies and policy interventions will be required at different stages of the hydrogen value chain. The cost-effective analysis should take into account the entire lifecycle of the fuel, from production to end-use. Among other factors, this analysis will help determine the extent to which the production of hydrogen-based fuels and fuel cells should occur on an international scale. Policy packages, rather than isolated policies, should be prioritized when establishing zero-emission ferry routes, requiring a collaborative and transnational approach. These policy packages should also explore methods for mitigating risks for early adopters, launching new projects, and developing infrastructure.

As potential avenues for future research, case studies could be conducted to analyze the implementation of hydrogen and fuel cell technologies in specific maritime regions, companies, or ship types. Economic analyses can also be undertaken to evaluate the financial aspects associated with the adoption of fuel cells and hydrogen in the maritime sector. Additionally, investigating supply chain and infrastructure development, particularly in the context of hydrogen bunkering—a significant challenge hindering widespread adoption in the maritime industry—could serve as another fruitful research topic. Lastly, examining public perception and attitudes toward hydrogen and fuel cell technologies in the maritime sector could provide valuable insights to shape forthcoming regulations.

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