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Overview of the Use of Hydrogen Fuel Cells in the Maritime Sector

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ABSTRACT

Abstract The maritime industry, responsible for 80% of all global trade and 3% of all greenhouse gas emissions, has been aiming for decarbonization for decades. With the International Maritime Organisation (IMO) aiming for net-zero carbon emissions by 2050, the implementation of the use of eco-friendly fuel and technologies has fast established itself as a priority. Hydrogen fuel cells, a new technology facing research and development, are one such alternative fuel source that has zero-carbon emissions. This paper presents a technological overview of the types of hydrogen fuel cells, the ship structural requirements for their storage and transport, the challenges associated with implementing this technology, and examples of ships currently using hydrogen fuel cells. Also provided is an in-depth analysis of hydrogen fuel cells with alternative fuels like ammonia and biofuel and with fossil fuels like heavy fuel oil (HFO) and liquified natural gas (LNG).

Keywords: *Hydrogen, Hydrogen Fuel Cells, Maritime Sector, Decarbonization, Types of Fuel Cells, Comparison of Fuels, Ship Requirements.*

1. INTRODUCTION

Currently, one of the most profoundly impactful issues faced by the modern world is the issue of global warming. Defined as the long-term increase in the Earth's average surface temperatures, global warming is brought about by various anthropogenic and natural factors. In fact, in its 2013 fifth assessment report, the Intergovernmental Panel on Climate Change (IPCC) documented that "It was extremely likely that more than half of the observed increase in global average surface temperature" from 1951 to 2010 was caused by human activity[1]. Because of this profound human factor, many national and international agencies scrambled to implement new policies to reduce their global greenhouse gas (GHG) emissions. One of the agencies included in this list is the International Maritime Organisation (IMO).

The maritime industry is responsible for nearly 3% of all GHG emissions, and is on a trajectory to increase its share to 10% by 2050[2]. According to recent UN Trade and Development (UNCTAD) statistics, ships transport and carry out nearly 80% of global trade from ports to sea[3]. In order to facilitate this cargo, they employ the use of various engine and power system modules. These engines are inevitably fuelled chiefly by fossil fuels like heavy fuel oil (HFO), Marine diesel oil, or LNG which release harmful NO_x, SO_x, and CO_2 emissions. The maritime industry is estimated to rely on roughly 300 million tonnes of polluting fuels, with 90% of this being utilised by 90,000 marine vessels[2]. Because of the shipping industry's palpable environmental impact, the IMO implemented new policies to aid in its decarbonisation to help reduce this impact.

The IMO implemented regulations under Annex VI, titled 'Regulations for the Prevention of Air Pollution from ships' of the International Conventions to prevent pollution from ships (MARPOL). They aim for net-zero carbon emissions by 2050 according to new policies introduced in 2023[4].

One of the ways to achieve this net-zero emissions goal is the use of alternative fuel. Alternative fuels like ammonia, hydrogen and methanol emit considerably less greenhouse gases. Their widespread use has the potential to greatly reduce the maritime industry's environmental impact. Among them, hydrogen is a fuel that is fast gaining attention because of its high energy density. Already being used in sporadic projects in the maritime industry and the transport industry in general, hydrogen is used in relation to many other technologies and devices, including fuel cells.

Hydrogen fuel cells are fast-emerging energy saving devices with roots dating back to the 1960s[5]. Despite their old origin, hydrogen fuel cells have still not reached a level of development that will allow their use in an extensive sense throughout the maritime industry. Insufficient information and only minimal usage of these fuel cells have proved as challenges towards their practical implementation. Despite this, hydrogen fuel cells have great potential to decarbonise the shipping sector. Utilising simple chemistry, fuel cells only produce water, heat, and electricity as byproducts[6]. Without any emission of greenhouse gases, these devices could revolutionize the maritime industry.

2. HYDROGEN FUEL CELLS

Fuel cells are devices that continuously convert oxidizing fuels (hydrogen, methane, etc.) into electricity with heat and water as the sole byproducts through electrochemical processes [6]. Hydrogen fuel cells exclusively use hydrogen as a fuel source. In contrast to the widely used diesel engines in ships, fuel cells mitigate the indirect route of the utilization of thermal energy. This reduces noise and vibration, which is highly advantageous for both commercial and military vessels [7].

It provides a promising substitute to diesel-fuelled engines that use fossil fuels by mitigating the production of No_x So_x, and Co_2. Producing no greenhouse gases and minimum waste, the development of hydrogen fuel cells proves to be greatly advantageous as an alternative[7,8].

2.1 Principle of a Hydrogen Fuel cell.

Fuel cells are fundamentally similar to the structure of batteries and function under the same working principle. Although their operational mechanisms differ, both of them are modular in nature. Batteries typically execute both the function of energy conversion and storage where electroactive materials are embedded into the electrode structure [7,9].

The heart of a fuel cell is a membrane electrode assembly (MEA) comprising a proton exchange membrane (PEM) present between two electrodes, an anode and a cathode[10,11]. The anode and cathode are typically carbon based and coated with platinum to ensure they remain neutral and do not participate in the reaction. The hydrogen is supplied to the anode and oxygen is supplied to the cathode. When this happens, hydrogen molecules get split into protons (H^+) and electrons (e^-) in a transformative process. The protons move toward the cathode through the PEM while the electrons are forced through an external circuit, thus generating an electrical current. At the cathode, the protons combine with oxygen atoms and form water in an exothermic reaction[12]. An individual fuel cell produces very small amounts of energy, about 0.7 volts.

Because of this, fuel cells are typically arranged in series called 'fuel cell stacks' to produce sufficient energy[4].

The overall chemical reaction is termed as reverse electrolysis and can be represented as:

$2H_2 + O_2 \rightarrow 2H_2O$ + electricity + heat

This process is highly efficient and eco-friendly. Because they are not associated with the creation of greenhouse gases, they have the potential to significantly alter the carbon output released by the maritime industry[13].

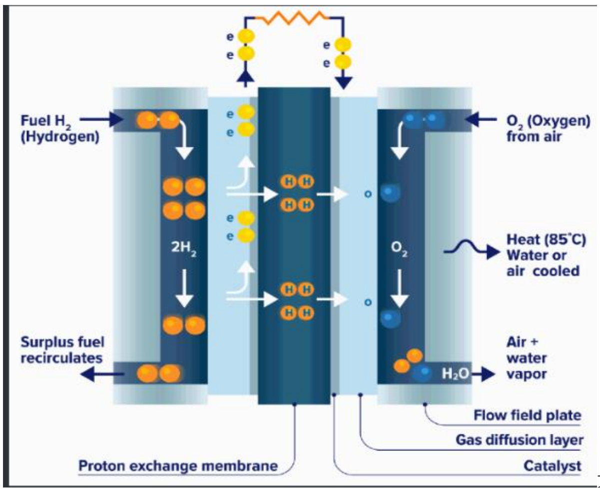

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Fig-1: Fuel cells

3. TYPES OF FUEL CELLS

Various fuel cells have been developed till date and are differentiated on the basis of the type of electrolyte they use. The types of fuel cells include Proton Exchange Membrane Fuel Cells (PEMFC), Solid Oxide Fuel cells (SOFCs), Direct Methanol Fuel cells (DMFCs), Alkaline Fuel cells (AFCs), Molten Carbonate Fuel Cells (MCFCs), and Phosphoric acid Fuel cells (PAFCs). Among them, only PEMFCs and AFCs are hydrogen fuel cells, though DMFCs are also discussed because of their rising popularity in the maritime industry.

3.1 Proton exchange membrane fuel cell

PEMFCs are the most commonly used type of fuel cells. They are highly efficient, achieving up to 50-60% conversion efficiency even with just a few kilowatts. When fuelled directly by hydrogen, they also boast high energy densities and net-zero pollutant emission[7].

PEMFCs use a polymer electrolyte membrane as the PEM, distinctly differentiating it from SOFCs and AFCs. Their low operating temperatures (60-100℃) allow for quick start-ups, safe usage, and the utilisation of less stringent materials[8]. Among the diverse types of fuel cells, membranes based on perfluoro sulfonic acid polymers like Nafion™ are most successful because of their good conductivity[14.]

However, their main disadvantage is that these types of fuel cells are susceptible to electrode poisoning by CO and CO_2 contamination. This is showcased in the case of CO because of its high surface absorption at low temperatures [7,14]

Ships like the Hydrogenesis, a ferry ship in Norway, the Hydrogen One (a cargo ship), and Sea Change (ferry ship in the USA) are some examples of ships that utilise PEMFC technology[5].

3.2 Solid Oxide Fuel cells.

As compared to PEMFCs, SOFCs work at a much higher temperature range, between 600-1000ºC.[7] SOFCs use a Yttria stabilised Zirconia electrolyte at its core, which is solid and ceramic, making it particularly unique.[158] Out of all the types of fuel cells, the SOFCs hold the most potential because of their extremely high efficiency and low operating costs. Along with near zero carbon dioxide emissions, no NO_x or pollutant formation, SOFC power systems also require one-third the amount of water associated with normal combustion fuels.[16,17] Although primarily fuelled by hydrogen, SOFCs may also be fuelled by biogas, natural gas, hydrocarbons, and methanol.

With various countries trying to optimise on SOFC technology, one of the leading programs that have emerged is the SOFC program initiated by the United States of America. This project aims at the creation and development of SOFC technology for both large scale and small-scale modular systems while maintaining low costs. Started in 2000, this program is still underway and their major contributions include the development of a 200 kWe SOFC prototype system and the state of the art (SOA) anode supported planar SOFC technology.[16]

So far, however, the limited development state of SOFCs, their current high operating costs and their mechanical vulnerability has prevented SOFCs from being widely adopted[7].

3.3 Alkaline Fuel Cells

AFCs were one of the first fuel cell technologies developed and the first to be widely used in space programs. The electrolyte used in AFCs is a solution of potassium hydroxide in water with about 30% concentration[18]. They are fuelled by both hydrogen and ammonia and are closely related to PEMFCs except that they use an alkaline membrane instead of an acid one. This contributes to their high energy efficiency, which exceeds 60% on a regular model[19,20]

Just like in PEMFCs, AFCs are susceptible to CO_2 poisoning. Further issues including low weatherability and problems regarding different pressure requirements are addressed by the Alkaline Membrane Fuel cell (AFMC). AFCs were first used in the Hydra, but are not preferred over PEMFCs because of their significant drawbacks[5,19]

Table-1: Comparison of the types of hydrogen fuel cells

Cell name	Electrolyte	Electrolyte Type	Efficiency
Proton Exchange Membrane Fuel Cell (PEMFC)	Polymer electrolyte membrane	Solid	50-60%
Alkaline Fuel Cell (AFC)	Potassium Hydroxide solution	liquid	60-70%
Solid Oxide Fuel Cell (SOFC)	Yttria-stabilized Zirconia (YSZ)	Solid	50-75%

4. SHIP REQUIREMENTS

Because of the flammability of hydrogen gas, it is essential to follow specific ship design and layouts to ensure the safety of the crew. In a recent 'Discover Zero' ship retrofitting project, safety measures were extensively discussed regarding hazardous zones to fuel cell spaces[21].

The fuel cell space is the enclosure containing parts of or whole of the fuel cell power system. Because of the flammability of hydrogen gas, this space is associated with various safety procedures and devices. These safety procedures are discussed below.

4.1 Access

Fuel Cell Spaces should be designed for automatic operation without the risk of hands-on maintenance personnel. Along with safe removal procedures and routes, the fuel cell space should be designed in such a way as to allow remote shut down of the area in case of failure of the system. The ship should also be fitted with a bunkering Emergency Shutdown (ESD) system[22].

All auxiliary systems for fuel cells which contain primary or reformed fuel in such an arrangement as to allow potential leakage into the main system should be provided with appropriate extraction and detection technologies[23]. It should allow for the ventilation of gaseous fuels into the open deck, and its structure should also be designed to prevent the accumulation of hydrogen or other gases. If all these regulations are followed, then an air lock is not mandatorily required. Though if no direct access to the fuel cell space is available from the open deck, then an air lock is required[22,24].

4.2 Atmospheric control and ventilation

Any ducting ventilation utilized by the fuel cell space should not serve any other space and should be equipped with two or more fans. They should provide 100% redundancy upon the failure of one fan, though in this case the fuel system should shut down[24].

The ventilation rate in fuel cell spaces should be sufficient to dilute the average gas/vapor concentration below 25% of the lower explosive level (LEL) in all leakage scenarios. Ventilation air inlets for non-hazardous spaces should be at least 1.5m away from the boundaries of a hazardous zone[22].

Any combination of an aluminium or magnesium alloy and a ferrous fixed or rotating component is to be considered a sparking hazard and is not to be used[24].

4.3 Fire safety

Fuel Cell spaces are to be fitted with a suitable fixed fire extinguishing system (FFES) appropriate to the fuel material and chemistry being used[25]. Pressure and temperature should be closely monitored to prevent the outbreak of fire[23].

Air inlet and outlet vents should be provided with fail-safe automatic closure mechanisms upon the detection of fire, and fire dampers should be installed. This mechanism should be periodically tested to verify their functionality[22,24].

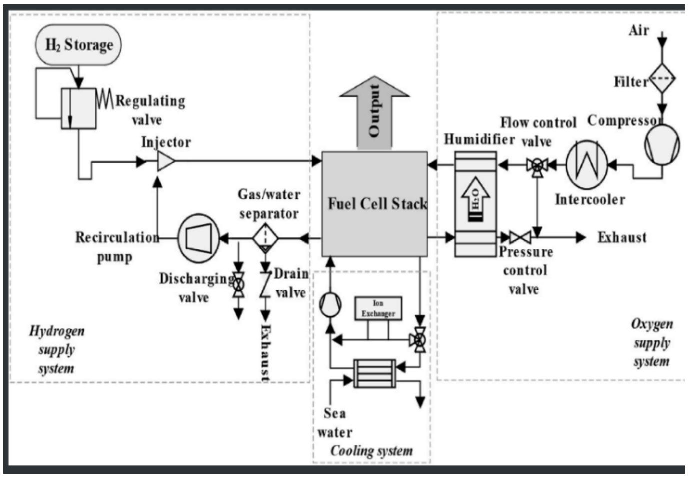

Fig-2: Fuel Cell Power System in a ship

5. CHALLENGES IN IMPLEMENTATION

Hydrogen fuel cells are not devices that are used extensively in the maritime sector. Although a remarkable solution to the issue of climate change, it is under inspection, testing, and development. This limited boundary of usage restricts these fuel cells under ctegories like durability, safety, and incorporation. All these factors are discussed below.

5.1 Vessel layout

In order to accommodate FC systems and follow regulations and policies, ships are usually constructed with these in mind instead of implementing them in preexisting vessels. Retrofitting ships is fairly rare, because of its impracticality and high costs. Among the 50 identified hydrogen-fuelled marine vessels, only 10 have been retrofitted[18]. Notable examples of retrofitting ships include H2 barge 1 and H2 Barge 2, which are both inland container vessels. However, to make space for the voluminous hydrogen systems, they lost around 16 TEU of cargo space[26]. This loss of cargo space is an important factor that discourages various engineers and investors from retrofitting ships.

Although in the case of H1 barge 1 and H2 barge 2, it was argued that this was an acceptable trade-off for reduced environmental damage, many traders refuse to adopt methods that compromise their businesses, thus bringing into question its practicality.

86% of vessels are less than 50m long, making it tougher to implement the distance regulations required for fuel cell spaces[18]. The spaces required for ventilation outlets, inlets, and widths are sometimes not compatible with ship designs. Due to limited deck spaces, many vessels cannot or do not comply with these regulations. Notably, the inland vessel, the Three Gorges Hydrogen Boat No.1 opted for a reduced distance between its hydrogen tanks and outer shell plating, set at no less than 1m from the ship's side[27]. This distance is shorter than the one specified in the IGF regulations[18]. Thus, it proves hard to maintain hydrogen safety precautions in small vessels.

5.2 Safety

The safety precautions and risk assessment primarily depend on the type of fuel, type of ship, ship layout, and fuel cell space[4].

Safety risks aboard hydrogen-powered ships are usually related to the properties associated with the element. Its high flammability, low density and ignition energy, and high ignition velocity can lead to small explosions, especially in enclosed spaces. Ammonia, methane, and hydrogen require gas-tight pipelines and storage tanks and constant monitoring. Although the IGF monitors bunkering situations, it does not provide a solution for large scale and rapid bunkering situations[21].

Bunkering is the process of supplying a ship with fuel. Hydrogen bunkering contains inherent risks including but not restricted to hose ruptures and valve leakages often caused by corrosion or strength failure[18,28]. To counter this, authorities have recommended shortening hose length, and adding mechanical protection around it to prevent corrosion[21].

5.3 Incorporation

Although more efficient and eco-friendlier than traditionally used fossil fuels, hydrogen fuels are still hard to incorporate into existing infrastructures. Hydrogen's small molecular structure can cause brittleness in materials not specifically designed to handle it[29,30].

Its lower energy density also means that more hydrogen is required as compared to natural gas, adding the danger of hydrogen transportation. In order to build hydrogen pipelines or storage facilities for refuelling ports, large capital investments and logistical data is required[30].

This discourages many prospective builders and investors, impeding the decarbonization of the marine sector. Economically speaking, there is no market encouragement for the creation of infrastructure for hydrogen fuel since very few ships are fuelled by it. Although IMO has set stringent targets, there is still a long time before hydrogen fuel cells can be widely used.

5.4 Costs

Hydrogen is an incredibly costly fuel to produce. The following statistics will be presented using levelized costs of hydrogen (LCOH), which is a methodology used to account for all of the capital (CAPEX) and operating (OPEX) costs of producing hydrogen. It is presented in USD/kg. of hydrogen[31]. While grey oxygen is the least expensive to produce (USD 0.67-1.31 per kilogram), but is unsustainable because of its high emissions. According to the International Energy Association (IEA)[32], its production method (SMR) is cheapest in the Middle East, United States, and Russia. It is most expensive in China. Blue hydrogen costs between 0.99-2.05 USD, but is more sustainable. Green hydrogen, a zero-emission fuel, is the costliest, being between 2.28-7.39 USD/kg because of the high cost of electrolysis involved in its production[30,31]

5.5 Durability

Durability refers to the lifetime of fuel cell stacks. According to a report by the company NedStack™, it can build PEMFCs with lifetimes of 24,000 hours and around 4,000 hours for inland shipping vessels[33]. Its lifetime is affected by the loss of catalyst, reduced conductivity of electrolytes, corrosion, poisoning, and flooding. The lifetime of SOFCs is affected by loss of catalyst, cracking, and corrosion. Because of issues of durability, the large-scale commercialization of hydrogen fuel cells is tough since it adds to maintenance costs[4].

6. COMPARISON OF FUELS

Given below is a comprehensive comparison of hydrogen fuel cells with both fossil fuels and alternative fuels.

6.1 Comparison with fossil fuels

Currently, 90-95% of the maritime industry uses fossil fuels as its primary fuel source. This encompasses heavy fuel oil, marine diesel oil and liquified natural gas (LNG). They are cheaper, more easily available, and have a more extensive existing infrastructure as compared to hydrogen fuel cells[10]. However, they are a significant contributor to global warming because of the CO_2, SO_x, and NO_x emissions associated with them. Currently, the shipping industry is responsible for 3% of the total greenhouse gas emissions around the world. Because of this and the regulatory regulations of the IMO, various shipping companies are now advocating for the use of alternative fuels[34].

According to IMO restrictions, Sulphur content in marine fuels cannot exceed 0.5% by mass after January 2020. This means that ships can use heavy fuel oils with reduced sulphur content, or switch to low-sulphur fuels like LNG or alternative fuels. Another option allows ships to continue using heavy fuel oil if they have an exhaust gas cleaning system installed which removes the sulphur from the exhaust before releasing it into the atmosphere[35].

6.2 Heavy Fuel Oil (HFO)

Heavy fuel oil (HFO) is a fuel source that has been in widespread use since the 1960s. It is about 30% cheaper than any alternatives and is used in all types of vessels, from cargo ships to cruisers. Despite its extensive use, however, HFO is one of the most harmful fuels that could be used because of both SOx emissions and the creation of black soot termed as black carbon. Formed by the incomplete combustion of HFO, black carbon absorbs sunlight while airborne, which, when landing on frozen substances like ice or snow, causes them to melt. Black carbon is estimated to have the greatest effect on global warming after carbon dioxide[35]. HFO's relation with black carbon is a major contributing factor to the ban on the use of HFO fuel in the Arctic, which came into force on July 1, 2024. This ban eliminates the risk of oil spills in the Arctic, and also prevents the creation of black carbon near polar regions. The ban on the use of HFO is also in place in the Antarctic, and in the national parks in the Svalbard Archipelago in Norway[35,36].

6.3 Liquified Natural Gas (LNG)

LNG is used by around 5-8% of the marine industry as a fuel source.

It is more eco-friendly than the other fossil fuels used, with significantly less emission produced compared to them and has the potential to reduce CO2 emission by nearly 25%[37]. However, the main disadvantages of LNG are its affinity for methane slips and lack of infrastructure. The initial costs for LNG pipelines and storage facilities are immense, but its cheap maintenance costs, and reduction in long-term environmental repercussions makes it a tempting alternative. Although Hydrogen has lower emission rates, LNG is still preferred[38].

6.4 Comparison with alternative fuels

Alternative fuels like hydrogen ammonia, methanol, or biofuels are an emerging substitute for fossil fuels. They are cleaner fuels with less GHG emissions. Among them, hydrogen and ammonia are fast gaining attention because of their long-term decarbonisation potential to operate as zero-carbon emission fuels. With more attention being given to their adoption and research, alternative fuels have begun gaining foothold for possible long-term usage[39].

6.5 Ammonia

Ammonia is one of the most commonly available synthetic chemicals in the world thanks to its production method; the Haber-Bosch process. In this process, nitrogen and hydrogen react to form ammonia with iron as a catalyst and molybdenum as a promoter under high temperature (400-500°C) and pressure (150-300 atps) conditions. Its chemical equation is given below

$N_2 + 3H_2 \rightleftharpoons 2NH_3$

Like hydrogen ammonia is also a zero-carbon emission fuel i.e. it is more or less just as eco-friendly as hydrogen fuel cells. The main difference and advantage hydrogen fuel cells enjoy over ammonia are their higher energy efficiency and energy densities[40]. While hydrogen enjoys an energy density of 120 MJ/Kg, ammonia has a density of 18.6 MJ/Kg. However, ammonia is less expensive and less dangerous to transport and store than hydrogen. Although liquid ammonia is toxic, it can still be stored in solid form in metal amine salts, ammonium carbonates, or even urea[4].

Because of the relative security of ammonia over hydrogen in terms of storage, an alternative solution was presented. Ammonia began being used as a hydrogen carrier. Ammonia contains 17.8% hydrogen by weight, making it a feasible hydrogen carrier. Hydrogen may be stored in ammonia through the Haber-Bosch process. Then, hydrogen may be extracted from it whenever and wherever it is required by heating ammonia to high temperatures. After this process, it is possible for residual traces of ammonia to remain in the hydrogen after decomposition, posing issues of purity and contamination. Although this is a solution to issues regarding hydrogen storage, it is not widely implemented. because of doubts on its sustainability and environment-friendliness[41].

6.6 Biofuels

Biofuels are those fuels derived from vegetable oil, animal fat, recycled cooking oil, etc. Biofuel options for fossil fuel replacement include Fatty Acid Methyl Esters (FAME) biodiesel, hydrotreated renewable diesel including hydrotreated vegetable oil (HVO) and Fischer-Tropsch (FT) diesel. In addition to cleanup of waste, biofuels mitigate GHG emissions by roughly 86% as compared to petroleum diesel. Even second-generation biofuels, which are derived from lignocellulosic materials like agriculture residue, can mitigate these emissions by 70-90% compared to HFO. However, concerns regarding direct and indirect land use associated with growing the raw materials biofuels require have been raised. Because of their potential to divert land required to feed general populaces, biofuels still face some public backlash[39].

7. CURRENT PROJECTS

The utilization of hydrogen-powered ships has gained attention in recent times. With the regulations implemented by IMO, along with various global policies regarding climate change, more and more investors are getting motivated to invest in and produce these ships. The decarbonization of the maritime sector is an ongoing project and although evident change can be observed, it is a time-consuming process.

Since the first hydrogen-powered vessel was launched in 2007 (the H2O), further exploration of this technology and its application was stilted. From 2000 to 2020, only one hydrogen-fuelled vessel was created. It was not until 2021 that this production frequency reached seven vessels per year till 2024[18].

Among the various hydrogen fuel cell powered vessels, the most notable one is the MF Hydra, the first liquid-hydrogen powered passenger vessel. Built in Norway in 2021, it uses both liquid hydrogen and a 200kW Fuel cell for propulsion. This ferry can carry up to 295 passengers, 8 crew members and 80 vehicles and sails a route triangular between Hjelmeland-Skip Avik-Nesik in Norway[42].

The Energy Observer, developed by France was launched in 2017 and was the first ship to use hydrogen fuel cells as its primary source of power[10]. It has travelled over 62,000 nautical miles, powered primarily by solar panels and a 70kW hydrogen fuel cell[43].

Another notable example is the Viking Libra. Currently under construction, this ship is expected to be delivered by 2026. It will be the first hydrogen fuel-cell powered cruise ship and is expected to hold 998 passengers[44].

With rapid upcoming development, it is inevitable that more and more hydrogen-powered ships will come into being. With several ongoing projects including the Viking Astrea, PowerCell MS-500 and Hanaria[18], greater attention and funding is going into the development of hydrogen fuel cells to aid decarbonise the maritime industry.

8. CONCLUSION

In conclusion, hydrogen fuel cells have revolutionary potential in the shipping industry, providing a green alternative to conventional fossil fuels. This paper highlighted the huge potential of hydrogen as a cleaner energy carrier, with emphasis on its high energy density and ability to reduce the vibration and noise in ships. The types of hydrogen fuel cells were explored, and a comparison was made between them and the other fuel sources used in the maritime industry. Also exploring the challenges in implementing hydrogen fuel cells, this paper detailed ships already using hydrogen fuel cell technology.

It can be clearly observed that although challenges involving infrastructure development, cost, and technology development exist, the greater funding and attention hydrogen fuel cells are receiving has great prospects with relation to R&D efforts. Cooperation among stakeholders, governments, industry heads, and research bodies is necessary to bring about a quicker shift to hydrogen-powered ships.

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