Maritime Technology and Research
https://so04.tci-thaijo.org/index.php/MTR

Review Article

Is hydrogen a decarbonizing fuel for maritime shipping?

Nitin Agarwala*

Centre for Joint Warfare Studies, New Delhi 110010, India

Article information
Received: March 12, 2024
Revision: May 9, 2024
Accepted: June 3, 2024

Keywords
Hydrogen,
Decarbonization,
Climate Change,
IMO

Abstract

To meet the targets for carbon emissions as laid out by the Paris Agreement, the International Maritime Organisation has experimented with several technological, operational, and incentive-based methods. However, to date, a viable and reliable method or technology has eluded humankind in meeting the desired carbon emission standards of the shipping industry. Since LNG, so far considered as a potent decarbonizing candidate, has fallen short, efforts to experiment with hydrogen as an alternative candidate for decarbonization have found traction with researchers. Using desk-based qualitative research, the author aims to analyze the use of hydrogen in the shipping sector as a means of achieving decarbonization. In doing so, the future use of hydrogen as an alternative fuel for the shipping industry to achieve net-zero emission targets is examined, evaluated, and discussed. The study shows that, while hydrogen as a decarbonizing fuel in the shipping industry has high potential, its use as a zero-emission fuel is feasible only if either the technology of hydrogen production using renewables advances, or increased taxations and subsidies make the costs comparable to currently cheaper production methods using fossil fuels.

1. Introduction

Climate change has been attributed largely to carbon emissions due to anthropogenic efforts. The main contributor of carbon emission is the use of fossil fuel (OECD, 2023), or hydrocarbons as they are called. This organic compound is made up of hydrogen and carbon atoms. When a hydrocarbon undergoes combustion in the presence of oxygen, the carbon atom associates itself to form CO_2, and the hydrogen atom forms water. It is this CO_2 that contributes to atmospheric pollution and, hence, climate change. While other greenhouse gases (GHG) also contribute to climate change, CO_2 has seen the steepest rise since the late 1700s to 2018, largely due to the increased usage of fossil fuels (Agarwala & Polinov, 2021).

To address this rapidly increasing climate change, the target at hand for humankind is a carbon-neutral future, thereby eliminating hydrocarbon fuels from the global power supply. Accordingly, the world community, through the Paris Agreement of 2015, aims to decarbonize businesses to well below 2 °C above pre-industrial levels by 2050, and pursue efforts to limit it to 1.5 °C. While shipping as an industry contributes to a mere 1.6 % of global carbon emissions, the International Maritime Organisation (IMO) in 2016 agreed to develop a comprehensive strategy to address GHG emissions emanating from international shipping.

Such a commitment has forced the IMO to experiment with fuel-based, technology-based, operation-based, and incentive-based initiatives (IMO, 2018a, 2018b). However, no clear winner of

Corresponding author: Centre for Joint Warfare Studies, New Delhi 110010, India
E-mail address: nitindu@yahoo.com

a solution has been shortlisted for the maritime shipping industry. Such initiatives have allowed the use of alternative fuels such as Liquefied Natural Gas (LNG), Liquefied Petroleum Gas (LPG), methanol, liquefied biogas (LBG), hydrogen, ammonia, methanol, ethanol, hydrotreated vegetable oil (HVO), nuclear power, and renewable energy sources such as wind, solar, etc., in place of the existing Heavy Fuel Oil (HFO) (Wang et al., 2023). Each of these fuels has their own advantages and disadvantages. While LNG was considered as a decarbonizing fuel for the shipping industry, studies show that it is not a net-zero compliant fuel over its full life-cycle, and can hence be best considered as a transitional fuel until a net-zero fuel can be identified (Agarwala, 2022a). Similarly, hydrogen (liquefied LH_2, or gaseous H_2) and ammonia have been identified as low- to zero-carbon fuels that have the required potential to power shipping vessels, while helping the industry meet committed carbon emission targets for 2050. It is, hence, important that the capability of hydrogen as a decarbonizing fuel for shipping industry be evaluated.

Since hydrogen exists in nature as a compound, it needs to be produced to be used as fuel. As a fuel, hydrogen can be produced by using conventional energy extracted from fossil fuels, biomass, water, or from coal, or using renewable energy. Of these, the most interesting option is through the electrolysis of water using fully renewable energy (Nikolaidis & Poullikkas, 2017). However, the presently developed hydrogen production processes are from natural gas and coal, thereby making the process carbon intensive and, hence, preventing hydrogen from being a net-zero carbon fuel over its life-cycle. If this process of hydrogen production can be made net-zero over its life-cycle, hydrogen can be the much awaited decarbonizing fuel to provide the required decarbonization. To use hydrogen as a marine fuel, either fuel cells or an internal combustion four-stroke engine running on hydrogen need to be used. Since fuel cells using liquid hydrogen (LH_2) or compressed hydrogen gas are commercially available, proven on land, and are scalable to high powers, the use of fuel cells running on hydrogen for ships makes great sense. However, issues such as the scalability of fuel cells need to be resolved.

Even though the use of hydrogen as an alternative fuel seems encouraging for the decarbonization of shipping in accordance with the commitments of the IMO, there are issues that plague its use. Some of these include advanced storage requirements, fire hazard mitigation, availability, high costs towards scaling production, and transportation infrastructure. Accordingly, this paper aims to analyze the use of hydrogen in the shipping sector as a means of achieving decarbonization. In doing so, the future use of hydrogen as an alternative fuel for the shipping industry to achieve net-zero emission targets is examined, evaluated, and discussed.

2. Understanding hydrogen as a fuel

The interest in using hydrogen as a fuel arises from the fact that it produces no CO_2 as by-product. When used in fuel cells it undergoes a chemical reaction and, when used in engines, it undergoes combustion; however, in both cases, it produces only water and heat as by-products. Between the two processes, hydrogen fuel cells are considered more efficient, as they do not produce tail-piece emissions.

Even though hydrogen is the most abundant element in the universe, it is not available in a form that can be used directly. To obtain pure hydrogen, it needs to be produced artificially from fossil fuel energy or renewable energy using processes, some of which are carbon intensive. Accordingly, depending on the production process, hydrogen can be divided into five different types when production uses fossil fuels, and into three when production is through renewable fuels, as seen in **Figure 1**. *Black hydrogen* is produced using coal as the energy source, and *brown hydrogen* when using lignite coal, while *grey hydrogen* is produced by the steam reforming of fossil fuels. This method uses natural gas (mostly methane), and produces nearly 95 % of hydrogen annually. The carbon footprint of this process is in between that of natural gas and coal. When hydrogen is produced using natural gas via pyrolysis, by separating methane into hydrogen and solid carbon dioxide, it is called *turquoise hydrogen*. When the processing plant includes Carbon

Capture Utilization and Storage (CCUS) technology, they are said to produce *blue hydrogen*. Since the by-product of these processes is CO_2, the process is not carbon-free.

On the other hand, when the source of energy used is renewable, hydrogen is produced using electrolysis (splitting water into hydrogen and oxygen using electricity), and is called *green hydrogen*. When the source of energy is nuclear, it is called *pink hydrogen*, and when the energy is mixed from a grid, it is called *yellow hydrogen*. Since no CO_2 is produced in this process, it is considered carbon-free. However, the electricity used should be from renewables to ensure a carbon-free process. The costs of producing green hydrogen is significantly higher than those for blue or grey hydrogen.

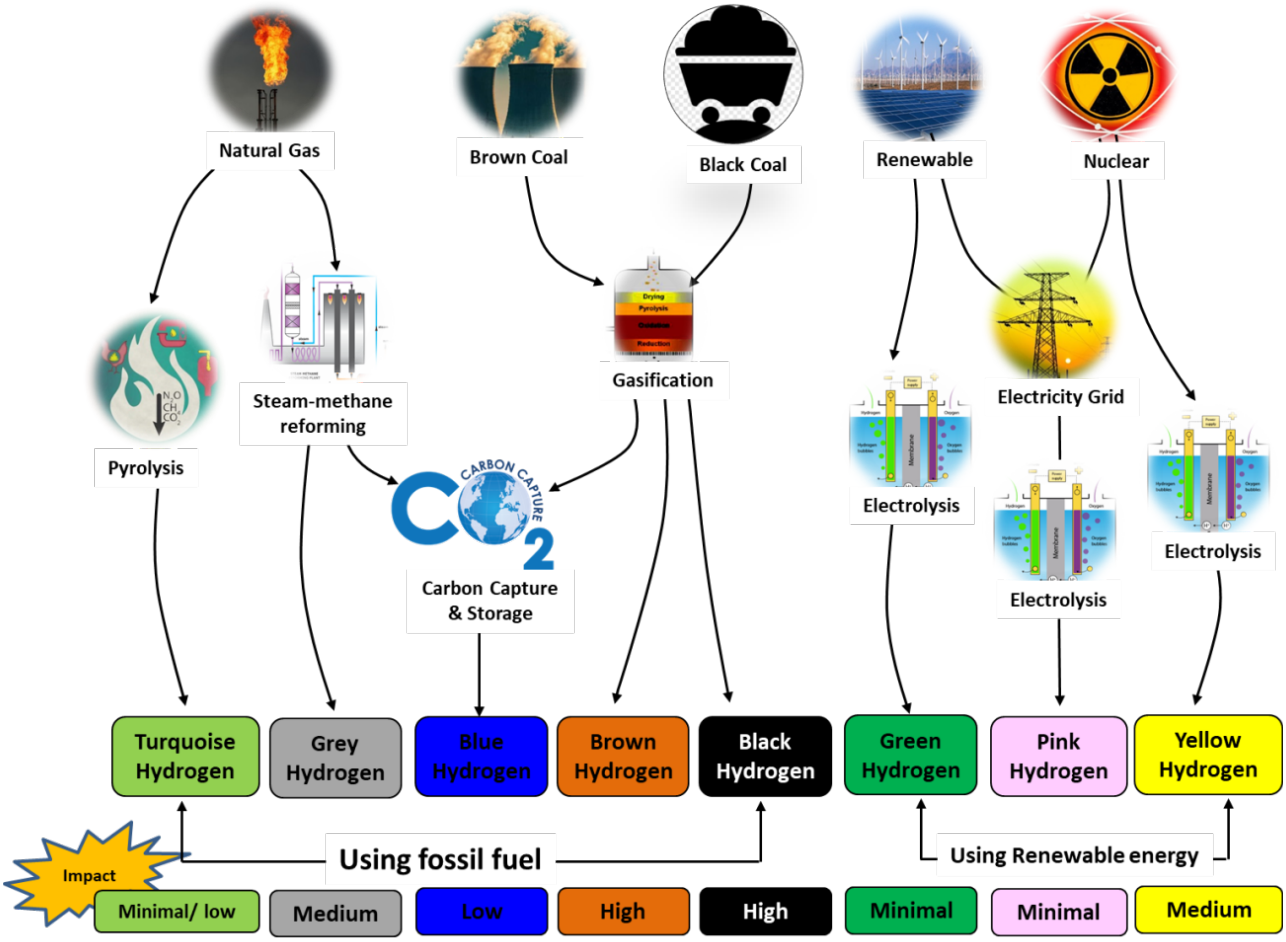

Figure 1 Production process for hydrogen (Source: Author).

Once the gas is produced, it needs to be stored and transported in fuel tanks. However, due to its very low energy density, it must be significantly compressed and cooled. Hence, hydrogen can be stored on a ship as a liquefied gas at –253 °C and with a slight overpressure; as a compressed gas at high pressure (typically 250 - 500 bar) in liquefied form at cryogenic temperatures; or bound to liquid or solid-state carriers (Hoecke et al., 2021). The type of storage is usually governed by the end use. When the requirement is low power and relatively short operational time, storage under pressure is the best solution. When the requirement is longer operational time and greater power, hydrogen needs to be stored under high pressure at cryogenic temperatures (Marine Services NORD, n.d).

Since the market for it is still developing, efforts are concentrated on addressing the clean, economical, and safe production and distribution of hydrogen.

Table 1 Comparison of fuel cell technologies.

Fuel Cell Type	Common Electrolyte	Operating Temp.	Typical Stack Size	Electrical Efficiency (Lhv)	Applications	Advantages	Challenges
Polymer electrolyte membrane (PEM)	Perfluorosulfonic acid	< 120 °C	< 1 kW - 100 kW	60 % direct H_2; 40 % reformed fuel	Backup power Portable power Distributed generation Transportation Specialty vehicles	• Solid electrolyte reduces corrosion and electrolyte management problems • Low temperature • Quick start-up and load following	• Expensive catalysts • Sensitive to fuel impurities
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	< 100 °C	1 - 100 kW	60 %	Military Space Backup power Transportation	• Wider range of stable materials allows lower cost components • Low temperature • Quick start-up	• Sensitive to CO_2 in fuel and air • Electrolyte management (aqueous) • Electrolyte conductivity (polymer)
Phosphoric acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150 - 200 °C	5 - 400 kW, 100 kW module (liquid PAFC) < 10 kW (polymer membrane)	40 %	Distributed generation	• Suitable for CHP • Increased tolerance to fuel impurities	• Expensive catalysts • Long start-up time • Sulfur sensitivity
Molten carbonate (MCFC)	Molten lithium, sodium and/or potassium carbonates, soaked in a porous matrix	600 - 700 °C	300 kW - 3 MW, 300 kW module	50 %	Electric utility Distributed generation	• High efficiency • Fuel flexibility • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Low power density
Solid oxide (SOFC)	Yttria stabilized zirconia	500 - 1,000 °C	1 kW - 2 MW	60 %	Auxiliary power Electric utility Distributed generation	• High efficiency • Fuel flexibility • Solid electrolyte • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Limited number of shutdowns

Source: (Office of Energy Efficiency & Renewable Energy, n.d)

3. Hydrogen as a marine fuel

As discussed, the two accepted forms of usage of hydrogen as a marine fuel is either as a fuel cell or through internal combustion in a four-stroke marine engine. Of these, the former technology is relatively advanced and proven on land-based systems, while the latter is specific to shipping and is currently under development, though some prototypes have already been produced (Bamford, 2023).

Though there are challenges that exist in carrying and using hydrogen onboard, a key feature that encourages the use of hydrogen as an alternative fuel is the relative ease with which existing ships can be retrofitted with hydrogen fuel cells. This has encouraged technology providers to look at ways and means of storing hydrogen at cryogenic temperatures and to rework the use of fuel cells onboard, both otherwise already common on land. Likewise, engine manufacturers are developing internal combustion engines that can use hydrogen fuel. However, to date, no large vessels have been tested with hydrogen as a marine fuel, due to the high cost of fuel cells and the limitations of the available technology to develop bigger fuel cells that can replace high power engines (Melideo & Desideri, 2024). Accordingly, their use has been limited to ferries and smaller vessels in the US, Belgium, France, and Norway (Marine Executive, 2019).

On the production side, a number of nations have invested in several hydrogen production projects in Europe, Australia, and China (Shell, 2022), as the gas is used extensively in industries. It is expected that the import and export of hydrogen will increase in the years to come, which would support decarbonizing strategies worldwide. Soon, ports will also aim to decarbonize themselves. The Port of Kobe in Japan is leading in this aspect, under a government strategy, by using hydrogen and ammonia and establishing itself as carbon-neutral by 2050 (Matthe et al., 2022).

Over the years, while several types of hydrogen fuel cells have been developed, there are several others that are currently under development, as seen in **Table 1**. Each one of them has their own advantages, limitations, and potential applications. The most common of the fuel cells is the polymer electrolyte membrane (PEM) fuel cell (Office of Energy Efficiency & Renewable Energy, n.da), which can be used for transportation, and requires hydrogen, oxygen from the air, and water for its operation.

While this technology develops, it is important to identify the marine vessels that can utilize these fuel cells, define the limit to power and energy demand these fuel cells can support, and identify the best role for these fuel cells in the propulsion plants of marine vessels. These, along with the storage and safety of hydrogen onboard ships, would eventually help confirm whether hydrogen can be a decarbonizing fuel for the shipping industry or not.

4. Challenges in using hydrogen as a marine fuel

Even though hydrogen qualifies as a strong candidate for being a decarbonizing fuel for the shipping industry, there are challenges that need to be addressed before its effective utilization (Marine and Offshore, 2021). These challenges exist onboard ship, during the production of hydrogen, and at the regulatory front.

Two main challenges for using hydrogen as a marine fuel are managing safety and storage. The need for *safety* arises both at the operational level and at the storage level due to the explosive and flammable nature of hydrogen. This necessitates the need for safety concepts for ship systems and the handling of these systems by crew. *Storage* is another area of concern, as hydrogen needs to be stored onboard under very high pressure and at cryogenic temperatures due to its low volumetric energy density as compared to other fuels. This requires additional efforts towards designing, developing, and maintaining such storage conditions on ships. In addition, studies show that, when hydrogen is used as a fuel in combustion engines, the efficiency reduces due to higher cooling water losses, and low brake-mean-effective-pressure is achieved due to the very low density of gaseous fuel. These demand an increase in engine dimensions to produce the same power at the same speed of a diesel engine (Seddiek et al., 2015). Furthermore, cooled spark plugs and a diluted hydrogen-air mixture are found to be better in eliminating the risk of detonation, with due consideration for defining the optimal layout and shape of an injector, such as the number of holes, their diameter, and their relative position (Falfari et al., 2023).

The existing inability to produce hydrogen through net-zero carbon methods is yet another challenge which needs to be addressed. This requires the use of renewable energy to generate green electricity that can be used to manufacture net-zero hydrogen. However, currently available systems still largely depend on fossil fuels for electricity generation. Though a number of projects aimed at using terrestrial (Agarwala, 2022b) and ocean (Agarwala, 2021) renewable energy are being planned and executed by various countries, they are yet to be realized in bringing about any substantial change. It thus becomes imperative to undertake a life-cycle cost analysis with a fuel cell combine, resolving storage and transportation issues and the cost of hydrogen production (Wärtsilä, 2022). Such a cost analysis over the entire life-cycle of hydrogen is considered essential for hydrogen to be accepted as a net-zero decarbonizing marine fuel.

Table 2 Known advantages and disadvantages of hydrogen as a fuel (Source: Author).

Advantages	Disadvantages
Properties	
Diffusion 3.8 times faster than natural gas	Odorless, colorless, tasteless
Rises at 20 m/s, which is 6 times faster than natural gas and 2 times faster than helium	Explosive range of 18.3 - 59 %
Most easily ignited at 29 % of H_2 in air	Ignition energy 0.02 ml
Less radiant heat	Flammability range of 4 - 75 %
	Blue flame
Safety	
	Accidents may get out of control
	Lack of emission and safety regulations
Fuel cell	
Fuel cells can operate for a long time	Very expensive raw material
Fuel cells can be used for several devices	Limited infrastructure for fuel cells available
Green Fuel	
Greenest energy source	Sensitivity to temperature changes might be a problem
Renewable and suitable	Low efficiency of 25 - 45 %
Almost no emissions	
No noise pollution	
No visual pollution	
Non-toxic	
Carbon free energy source	
Virtually zero-emission hydrogen production and processing	
Use of water for hydrogen production	
Maintenance	
Low maintenance efforts and costs	Energy required for liquefaction is high
	Storage of liquid hydrogen possible only for limited days due to high boil off
	Lack of filling infrastructure
	Lack of availability of hydrogen across the world
Management/ Policy	
	Limited knowledge/policies for procedure and filling time
	Non-availability of human resource for operating and maintain hydrogen systems
Technology	
Higher efficiency when compared to other energy sources	Limitation of retrofitting in all types of ships
Perfect for remote engines	Limitation in making bigger fuel cells that can replace higher power engines
Scalability possible by increasing capability of storage tanks	Not mature
Possibility of long-term energy storage	Not a reliable power source in current form
High energy density	Expensive technology
Possibility of using waste heat for utility purposes	Low durability of hydrogen devices
Quick charging possible	Limited involvement of the industry in developing technology
Could be used for advanced challenges	Extensive research required
	Storage issues exist

Table 2 (continued) Known advantages and disadvantages of hydrogen as a fuel (Source: Author).

Advantages	Disadvantages
Storage	
	Need to use compressors and high pressure tanks dedicated to hydrogen storage
	Large tanks required as low energy density in volume
	Danger of gas ignition or explosion in the case of a leak in the system
Cost	
Likely to become much cheaper in future	Transportation of hydrogen is quite expensive
Lower impact of world market prices of fossil fuels	High investment costs regarding hydrogen production and processing equipment
Lower dependence on other countries for fossil fuels	Expensive form of power production

On the regulatory front, existing international regulatory frameworks demand hydrogen-fueled ships comply with the International Convention for the Safety of Life at Sea (SOLAS) and Part A of the IGF Code, with ship owners needing to prove the safety of alternative design to the relevant flag administration. Though the IMO is working on adding hydrogen to the code, it remains a work in progress (Bakhsh, 2022). This, unfortunately, does not provide the required confidence to the ship owner that his vessel is actually safe, and would eventually be classified as safe for operations. Lack of such regulatory and policy uncertainties create operational uncertainties for ship owners and operators for the certification, inspection, or maintenance of new-age hydrogen-powered ships. Additionally, policies and incentives for the production and supply of hydrogen as a marine fuel are also considered essential, which are currently non-existent and, hence, an area of concern.

On the handling side, hydrogen handling demands high initial, operational, and handling costs. With a low volumetric energy density, it requires more space and weight for storage when compared to conventional fuel. Similarly, hydrogen, being highly inflammable and explosive, demands special precautions and standards, thereby increasing associated costs (Li et al., 2022). If hydrogen is to be used as a decarbonizing fuel, it is essential that these issues of 'hydrogen handling' are resolved without hurting the bottom line of operators.

The availability of hydrogen at ports can also be considered an issue but, due to the versatile nature of hydrogen, ports have started to develop their infrastructure worldwide to import and export hydrogen, to encourage the flow of hydrogen from ports to hinterland nations (Matthe et al., 2022). However, these ports will require additional infrastructure for storage, and energy intensive liquefaction and regasification, conversion, and reconversion systems.

Some advantages and disadvantages of the use of hydrogen as a marine fuel are discussed in **Table 2**, while known limitations of existing storage technologies are discussed in **Table 3**.

5. Producing hydrogen

Hydrogen is not available freely in the atmosphere. Hence, to be used as fuel, it needs to be produced. As discussed in Section 2, broadly, hydrogen can be produced from two sources: renewable energy and fossil fuel energy. The nature of the energy source and the ensuing process used will determine if the hydrogen produced is green or not. Accordingly, the produced hydrogen is of a number of types, as seen in **Figure 1**. Once this hydrogen has been produced, it needs to be stored for further use.

5.1 Processes

The broad process of manufacturing followed for hydrogen is seen in **Figure 2**. It may be noted that the bi-product produced when using fossil fuel is CO_2, while that when using renewable energy is O_2. Of these processes, green hydrogen is considered to have a minimal carbon footprint. Studies have shown that green hydrogen can be produced from water electrolysis (using alkaline electrolyzers (AE), proton exchange membranes (PEM), solid oxide electrolyzers (SOE), or photoelectrochemicals (PEC)) using intermittent renewable electricity (from solar photovoltaic, onshore wind, nuclear, or offshore wind) (Christensen, 2020).

Table 3 Technological barriers to known hydrogen storage methods (Source: Author).

Storage Technology	Advantages	Limitations
Compressed gas cylinders	Well understood up to pressures of 200 bar Generally available Low cost	Limited quantity can be stored at 200 bar Storage energy at 700 bar also lower than fossil fuels Higher pressure storage under development
Liquid tanks	Well understood Good storage density possible	Very low temperature requires good quality insulation High cost Losses through evaporation possible Energy stored incomparable to fossil fuels
Metal hydrides (Storage in solid state)	Some technology available Solid-state storage Can be made into different shapes Thermal effects can be used in subsystems Very safe	Heavy Can degrade with time Presently expensive Filling requires cooling circuit
Carbon structures	May allow high storage density Light May be cheap	Not fully understood or developed Early promise remains unfulfilled

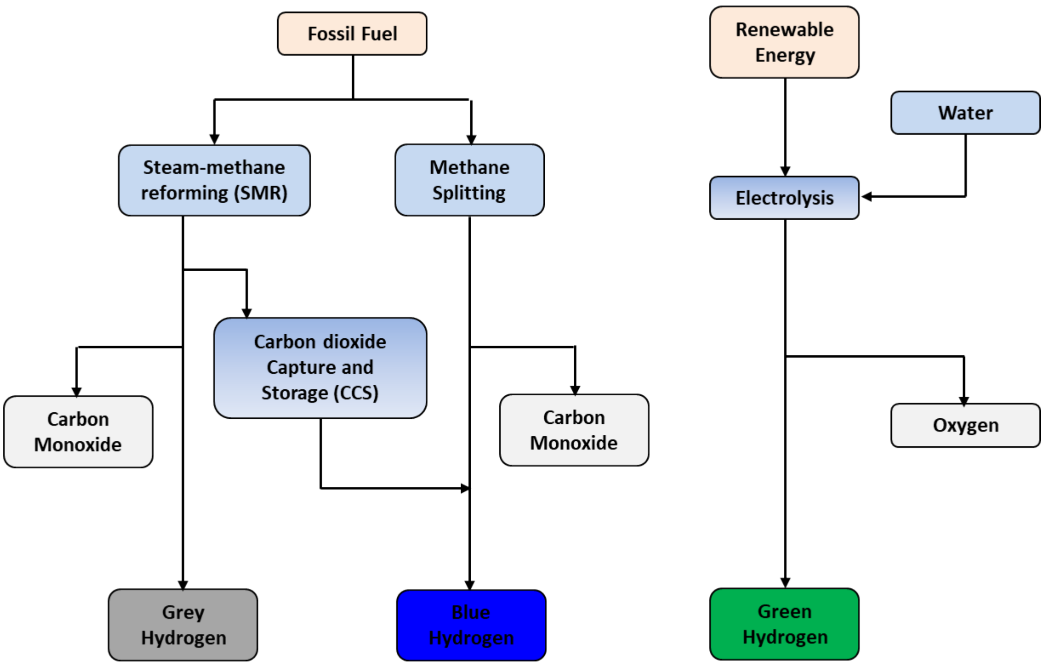

Figure 2 Hydrogen production processes (Source: Pathak et al., 2023).

5.2 Economic viability

The cost of manufacturing hydrogen from fossil fuel energy has been found to be lower than that from renewable energy (Shuit et al., 2009). Accordingly, grey hydrogen is priced at around USD 1–2/kgH_2, which is comparable to the cost of traditional fuel. However, grey hydrogen does not offer the sustainable reduction of GHG emissions. Blue hydrogen, on the other hand, is 30 - 80 % more expensive, and green hydrogen is 4 times the cost of grey hydrogen (Bartlett and Krupnick, 2020). As technology advances, and the cost of renewables and electrolysis reduce, the costs of green and blue hydrogen are likely to reduce. Such a change is possible only if there is a demand for blue and green hydrogen, which is feasible only when driven through government intervention.

5.3 Scalability of process

Based on the cost of producing it, it can be inferred that hydrogen from fossil fuel energy will continue to be used as a source of production as long as the technological barrier to reducing the cost of hydrogen from renewable energy is not lowered. Alternatively, if added burdens and reliefs, in the respective forms of taxation or subsidies, are provided to lower the cost of hydrogen production from renewable energy, the scalability of green hydrogen will become feasible. Accordingly, studies have shown that, if existing carbon pricing could be made direct, the process could be made scalable (Christensen, 2020). Another study shows that a carbon tax of USD 50 per ton of CO_2 would make the blue hydrogen price competitive with that of grey hydrogen (Bartlett & Krupnick, 2020).

5.4 Life-cycle analysis

Even though the processes of combustion and electrochemical conversion to produce hydrogen are environmentally benign, other stages of its life-cycle, such as production, transport, and storage, may not be. It is, thus, important to consider the cumulative burden of total consumption of primary energy resources on the environment to better appreciate the effectiveness of hydrogen as a decarbonizing fuel. This methodology is sometimes referred to as ‘cradle-to-grave’ analysis, and helps assess and identify the most promising and environmentally friendly option of an individual production. Such analysis aims to include direct and indirect environmental burdens related to industrial processes associated with the production and use of the fuel.

For life-cycle analysis, it is important to account for material production processes required to construct infrastructure used for the production of hydrogen. Accordingly, CAPEX and OPEX costs of all resources, emissions, and energy flows need to be inventoried, so that the total environmental picture can be derived. The well-to-tank emissions for the production of hydrogen from fossil fuel and renewal energy are different, and are shown in **Figure 3** (Spath & Mann, 2001; Mann & Spath, 2004).

Once produced, it needs to be transported to the place of use. The emission contribution of this would depend on the distance of the production plant to the point of usage and the mode of transportation used. However, this will be consistent for both production sources.

In the tank-to-wake region, storage energy needs to be considered individually, as they vary from one ship to another (Hoecke et al., 2021), while the energy for conversion will be negligible, and can be neglected.

5.5 Comparison with other marine fuels

To understand the advantages of hydrogen as a fuel, it is important that a comparison of it with other fuels is made. Accordingly, **Table 4** provides a comparison of the properties of various fuels. One notices that the heating value of hydrogen is the maximum and, hence, the amount of power generated by hydrogen will be the maximum when compared to diesel engines. This is because hydrogen has higher overall energy efficiency during fuel conversion and provided with regenerative breaking in power trains to improve efficiency. **Table 5**, on the other hand, provides the emission reduction achieved by various fuels when compared to the conventional fuel - diesel.

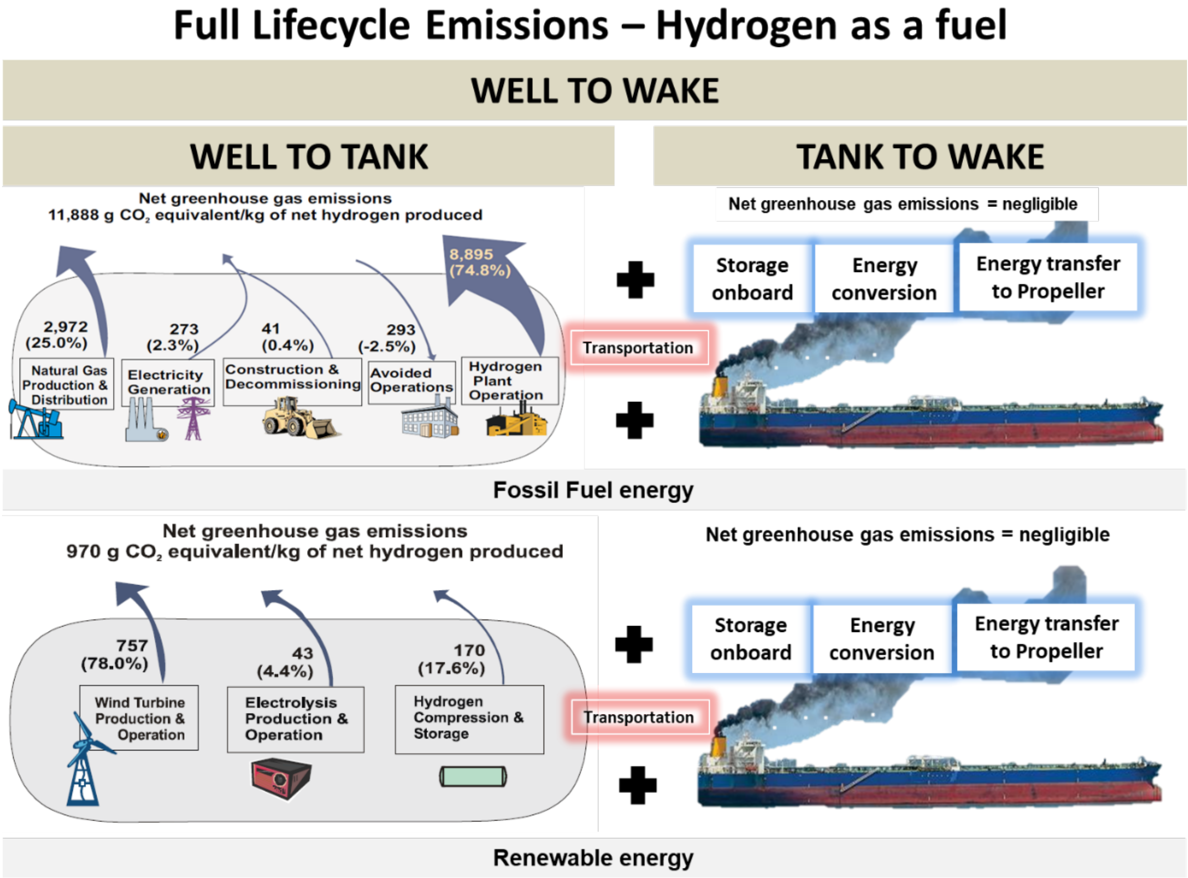

Figure 3 Full life-cycle emissions of hydrogen (Source: Author; Spath & Mann, 2001; Mann & Spath, 2004).

Table 4 Properties of various fuels (Source: Author, from various resources).

	Diesel	LNG	Hydrogen	Methanol	Ammonia	Ethanol
Density (kg/m^3)	837	443.5	0.082	790	0.730	789
Higher heating value (HHV) (MJ /kg)	45.8	50	141.9	22.7	22.5	29.7
Lower heating value (LHV) (MJ /kg)	43.25	50	120	20.09	18.8	27
Auto-ignition temperature (1C)	316	540	571	465	651	423
Flammability in air (vol%)	1 - 6	5.3 - 15	4.7 - 75	6.7 - 36	15 - 28	4.3 - 19
Laminar flame velocity (m/s)	0.867	0.38	3.51	0.54	0.015	0.47
Energy content (MJ/lit)	36.1	11.43	4.46	15.83	11.62	21.21
Max. particle compression ratio	23:1	17:1	17:1	19:1	50:1	19:1

Table 5 Emission reduction by alternative fuels as compared to diesel (Source: Author, from various resources).

	LNG	Hydrogen	Methanol	Ammonia	Ethanol
SOx	100 %		99 %	100 %	
NOx	95 %	100 %	60 %		10 %
PM	99 %			100 %	35 %
CO2			7 %		35 %
GHG	27 %	15 - 33 %	20 %	90 %	40 %

6. Regulations

Even while hydrogen has its own benefits as a decarbonization fuel for shipping, it is surprising that the International Maritime Organisation (IMO) does not have rules for the hydrogen design of ships. In place, they have provided a mechanism called the 'alternative design approach', which allows innovation without the need for rules. Such an approach requires that equivalent levels of technological safety be demonstrated by the innovator, as given by existing rules. However, realizing the importance of hydrogen and ammonia towards decarbonization of the shipping industry, the IMO sub-committee agreed to convene an inter-sessional working group in September 2024 to finalize the required guidelines (IMO, 2023).

6.1 Safety

Since regulations have not been defined explicitly, it is important that one appreciates the safety concerns associated with use of hydrogen as a fuel (Depken et al., 2022). The most important area of concern for hydrogen is its 'high combustibility'. With a wide range, and low auto-ignition temperature, hydrogen explosions are a major area of concern. To overcome this challenge, sensors may be used which are commercially available and usually of an electrochemical type. Such sensors are critical; hydrogen cannot be mixed with an odorant, as it can contaminate fuel cells, and a leakage may remain undetected, since molecules of hydrogen are smaller than that of the odorant.

Yet another area of concern is the release of hydrogen from pressurized containers due to explosive release caused by a fire hazard. To ensure safety from such an event, a pressure relief device (PRD) may be used, which would release the gas inside to a cylinder if the temperature was to rise beyond permissible limits.

The use of cryogenic temperatures to store hydrogen is yet another area of safety that needs to be addressed. Such cryogenic temperatures can cause embrittlement of the structure where it spills. These safety concerns can be addressed by the use of CFD tools for hazard prediction, improved design, and mitigation (Abohamzeh et al., 2021).

Realizing the importance of the need for safety standards for the use of hydrogen as a fuel, technical standards ENR 14002:2021 have been issued by the Technical Institute of Italy as a voluntary technical standard for using hydrogen as a fuel on naval vessels (ENR, 2021).

6.2 Compliance

Since the lack of rules and regulations cannot withhold innovations from developing alternative fuels for decarbonizing the shipping industry, the approach of 'alternative design' is being followed. However, this compliance is voluntary, and is not binding. Since the maritime industry is slow in adopting changes (Agarwala, 2022c), such voluntary compliance is usually incorporated at the retrofitting or design stage itself, as seen for a number of inland vessels where hydrogen has been used as an alternative fuel for propulsion (EU, 2018).

7. Discussion

Hydrogen, when used as a marine fuel, provides numerous benefits to ship operators, ship owners, the environment, and society by helping the shipping industry to meet carbon emission norms committed to by the IMO. In addition, hydrogen can provide lower fuel costs and a longer range when compared to conventional fuels, while stimulating development of new technologies and solutions for ship design, propulsion, storage, and safety. This could create new opportunities for collaboration among different stakeholders, such as energy producers, suppliers, regulators, and customers. However, like LNG (Wang et al., 2021) the cost difference of hydrogen in different countries is likely to impact the overall life cycle cost (LCC) of these ships.

While hydrogen produces negligible tail piece emissions, and can be considered a suitable decarbonizing fuel, using it on a ship has its own challenges, as discussed earlier. With nearly 300 kg of hydrogen providing the same energy as a ton of diesel, the space required onboard to store liquid hydrogen is nearly eight times more than that of MGO. While land-based storage facilities can be adapted for marine application, the available space onboard for fuel storage is limited, and can be a major challenge.

To add to this, high endurance requires hydrogen to be stored in liquid form at extremely low temperatures (–253 °C), making the process highly energy intensive, with additional requirements of high quality and increasing thickness of insulation. Even the process of boil-off prior to use is an energy intensive process, with additional hazards of explosion due to leakages. Oxygen generated from air condensation on pipelines is another explosion risk. While a similar setup as with LNG may be used for hydrogen, it will need greater focus on insulation and leakage avoidance.

Use of hydrogen in a number of inland shipping vessels has been experimented with, as seen in **Table 6** (EU, 2018). Due to technological limitations of not being able to produce large size fuel cells, these experiments have been limited to smaller vessels, mostly inland (Melideo and Desideri, 2024). This limitation has made use of hydrogen as a decarbonizing fuel for ocean going vessels a distant dream, and it will be some time before it can be realized. Due to increasing interest in hydrogen, classification societies have been forced to invest resources in developing studies for hydrogen fueled ships. The first rules for these ships were provided by Lloyds Register of Shipping in June 2023 (Blackmore, 2023) before other classification societies produced their own versions. Bureau Veritas (BV), one such classification society with regular involvement in developing hydrogen-fueled vessels by integrating hydrogen onboard cargo vessels and supporting fuel cells for shuttle passenger vessels, have even been able to publish a class notation for fuel cells (BV, 2022).

Though fuel cell technology is considered to be a matured technology, and the best suited, challenges remain in providing it hydrogen as a fuel for recharging. Similarly, when using hydrogen for combustion in engines, fuel blends with hydrogen of 25 % and more, complicate design, as classification changes from IIA to IIC in the IEC 60079 standard for handling flammable gas or vapor hazards, thereby forcing the use of low voltages in components, and dedicated fuel pumps for hydrogen pumping. Though Wärtsilä aims to launch the first retrofit package during 2023, and a pure hydrogen engine concept by 2025, it remains another work-in-progress (Koundal, 2023).

Despite the number of known and unknown challenges associated with the use of hydrogen as a decarbonizing fuel for shipping, an increasing awareness about climate change and a global demand for clean fuel are considered promising drivers for ensuring the use of hydrogen as a net-zero fuel for marine transportation. Although until 2018 most of the hydrogen being produced was used for industrial processes, and was never transported by ships like LNG, in February 2022, the world's first liquefied hydrogen cargo was transported between Australia and Japan (Synder, 2022), which is considered a major leap in ensuring the availability of hydrogen in distant places. Additionally, various ongoing and planned projects aim to demonstrate the feasibility of the use of hydrogen as a marine fuel, including those concerning engines (Wärtsilä, 2021). Such projects for large ships have tripled from 2019 to 2021 (Fahnestock and Bingham, 2021). This is being adequately supported by the development of advanced technologies and solutions for ship propulsion, such as solid oxide fuel cells (SOFCs) and liquid organic hydrogen carriers (LOHCs), for higher efficiency and energy density (Xing et al., 2021).

Since the advantages of hydrogen as a decarbonizing fuel are well established, waiting for technology to mature may not be a solution. In place, smaller power loads, such as ancillary systems, could be replaced with hydrogen fuel cells to reduce overall demand on the main engine, thereby reducing overall emissions from the ship (Melideo & Desideri, 2024).

Table 6 Use of hydrogen in inland shipping projects (Source: EU, 2018).

Project	Concept	Main Partners	Year	Fuel Cell	Capacity
FCSHIP	Assess the potential for maritime use of FC and develops a roadmap for future R&D for FC application on ships	DNV GL., LR, RINA, EU GROWTH program	2002 - 2004	MCFC, SOFC, PEM	
Class 212A/214 Submarines	Hybrid propulsion using a fuel cell and a diesel engine	CMR Prototech, ARENA-Project, Thyssen Krupp Marine Systems, Siemens	2003 - present	PEM	306 kW
New-HShip	Research project on the use of hydrogen in marine applications	INE (Icelandic New Energy), GL, DNV, etc.	2004 - 2006		
FELICITAS	PEFC-Cluster-improving PEFC reliability and power level by clustering	NuCellSys, PhG IVI, CCM	2005 - 2008	PEM	
ZemShip - Alsterwasser	100 kW PEMFC system developed and tested onboard a small passenger ship in the area of Alster in Hamburg, Germany	Proton Motors, GL, Alster Touristik GmbH, Linde Group etc.	2006 - 2013	PEM	96 kW
Cobalt 233 Zet	Cluster System Sport boat employing hybrid propulsion system using batteries for peak power	Zebotec, BrunnertGrimm	2007 - present	PEM	50 kW
E4Ships Toplaterne	Support of IGF Code development to include a fuel cell chapter and set regulatory baseline for use of marine fuel cell systems	DNV GL., Meyer Werft, Thyssen Krupp Marine Systems, Lürssen Werft, Flensburger Schiffbaugesellschaft VSM	Phase1: 2009 - 2017 Phase2: 2017 - 2022		
MF Vagen	Small passenger ship in the harbor of Bergen	CMR Prototech, ARENA-Project	2010	HTPEM	12 kW
Nemo H2	Small passenger ship in the canals of Amsterdam	Rederij Lovers etc.	2012- present	PEM	60 kW
Hornblower Hybrid	Hybrid ferry with diesel generator, batteries, PV, wind, and fuel cell	Hornblower	2012- present	PEM	32 kW
Hydrogenesis	Small passenger ship which operates in Bristol	Bristol Boat Trips etc.	2012 - present	PEM	12 kW
RiverCell - Elektra	Feasibility study for a fuel cell for hybrid power supply of a towboat	TU Berlin, BEHALA, DNVGL, etc.	2015 - 2016	HTPEM	-
SFBREEZE	Feasibility study of a high-speed hydrogen fuel cell passenger ferry and hydrogen refueling station in San Francisco Bay area	Sandia National Lab., Red and White Fleet	2015 - present	PEM	120 kW per module total power 2.5 MW

Source: EU (2018)

8. Way ahead

More testing is needed to address the safety aspects of handling, storage, and bunkering of hydrogen, especially when there is a leak. This would help define the size and layout of space required, and the additional fans and ventilation that would need to be provided onboard ships, thereby requiring design changes in the ship parameters. However, such additional space would be at the cost of cargo, the loss of which would need to be compensated for with ship operators through some incentives.

Being a unique gas that has to be stored under cryogenic temperatures requires special materials and connections. While these have been used on land-based systems, extrapolating them to the marine environment for ships by ensuring adequate strength, safety, and ease of operations would need additional scholarship.

While studies and work on regulatory framework are in progress, the immediate need to decarbonize maritime shipping cannot be overlooked. It is, hence, essential that frameworks such as alternative design process be used (DNV, 2021). This is a risk-based approval process in line with SOLAS Chapter II-2, and is described in the IMO Guidelines for the Approval of Alternatives and Equivalents (MSC.1/Circ. 1455). It is evaluated with the goals and the functional requirements of the International Code of Safety for Ship Using Gases or Other Low-Flashpoint Fuels (IGF Code, Part A). It requires project owners to actively demonstrate how the hazards and consequences are managed, instead of demonstrating passive compliance with existing rules. Such an approach may be the best tool to help materialize such new projects and allow innovations to continue.

While research continues, the role and support of policy-makers cannot be overlooked. To create greater interest in the industry to invest in research and development in hydrogen, green hydrogen has to be made cost-competitive with traditional fuel, for which government support is considered essential. A 2020 study (Christensen, 2020) of the International Council on Clean Transportation shows that the cost of producing green hydrogen from renewable electricity in the United States and Europe could be halved by 2050 with financial incentives to promote R&D, and more direct measures to price carbon could similarly accelerate the scalability of hydrogen (Bertlett & Krupnick, 2020). In addition, policies providing tax incentives to ship owners retrofitting ships with hydrogen fuel cells to compensate cargo volume loss, and increasing taxation on grey hydrogen, would help a faster growth of the green hydrogen industry (Reinsh & O'Neil, 2023).

While research on hydrogen continues worldwide, the need exists to harmonize such research efforts internationally to ensure a unified set of standards that would help the channelizing of efforts for addressing the technological challenges associated with the use of hydrogen onboard ships. Since storage of hydrogen onboard ships is one of the major challenges, innovative ways of developing electrolyzers (IRENA, 2022), producing hydrogen (Dincer & Acar, 2017), including from seawater, have been reported (Gnanasekar et al., 2021). How best this process can be used commercially, for powering a ship, is still to be studied.

9. Conclusions

Hydrogen can be used for powering ships. As a fuel, hydrogen can be used in fuel cells or in combustion engines. While fuel cells require pure hydrogen, the available technology for combustion engines requires hydrogen blending with other fuels. The most common and greenest way of generating power from hydrogen is using hydrogen fuel cells. However, as discussed, challenges exist for each of the technologies, which continue to be studied by researchers worldwide. The paper has discussed the possibility of the use of hydrogen as a decarbonizing fuel for the shipping industry. It is noted that the present technology of producing hydrogen as a fuel is not net-zero over the entire life-cycle, with fossil fuels based production methods being more unfriendly than renewable energy based methods. However, due to the low cost of production, fossil fuel technologies will continue to be used, as tax burdens or subsidies do not encourage renewable energy methods. Another major area of concern is the limited availability of hydrogen globally. An important component of this decarbonization are ports, which have not been discussed in the present article. However, ports can become a major catalyst for developing the use of hydrogen, by becoming hubs for both the import and export of hydrogen, while ensuring bunkers for visiting ships. Though there are no ready solutions available for green hydrogen or the use of hydrogen on ships, there is no doubt that hydrogen is a very strong candidate for decarbonizing shipping. The use of hydrogen as a decarbonizing fuel is only likely to increase, especially with increased public backing for its use in shipping (Carlisle et al., 2023). However, existing challenges and barriers need to be overcome with the due support of policy makers and regulators.

References

Abohamzeh, E., Salehi, F., Sheikholeslami, M., Abbassi, R., & Khan, F. (2021). Review of hydrogen safety during storage, transmission, and applications processes. *Journal of Loss Prevention in the Process Industries, 72*, 104569. https://doi.org/10.1016/j.jlp.2021.104569

Agarwala, N. (2021). Powering India's Blue Economy through ocean energy. *Australian Journal of Maritime & Ocean Affairs, 14*(4), 270-296. https://doi.org/10.1080/18366503.2021.1954494

Agarwala, N. (2022a). Is LNG the solution for decarbonised shipping? *Journal of International Maritime Safety, Environmental Affairs, and Shipping, 6*(4), 158-166. https://doi.org/10.1080/25725084.2022.2142428

Agarwala, N. (2022b). Project Green Ports: Are Indian ports on the right track? *Maritime Affairs: Journal of the National Maritime Foundation of India, 18*(2), 15-36. https://doi.org/10.1080/09733159.2022.2143134

Agarwala, N. (2022c). Role of policy framework for disruptive technologies in the maritime domain. *Australian Journal of Maritime & Ocean Affairs, 14*(1), 1-20. https://doi.org/10.1080/18366503.2021.1904602

Agarwala, N., & Polinov, S. (2021). Curtailing anthropogenic carbon dioxide to meet the targets of the Paris agreement using technology support mechanisms. *Journal of Human-Centric Research in Humanities and Social Sciences, 2*(1), 1-24. http://dx.doi.org/10.21742/jhrhss.2021.2.1.01

BV. (2022). *NR 547 outlines requirements on the design, construction and installation of fuel cells systems*. Retrieved from https://erules.veristar.com/dy/data/bv/pdf/547-NR_2022-01.pdf

Bartlett, J., & Krupnick, A. (2020). *Decarbonized hydrogen in the US power and industrial sectors: Identifying and incentivizing opportunities to lower emissions*. Resources for the Future. Retrieved from https://www.rff.org/publications/reports/decarbonizing-hydrogen-us-power-and-industrial-sectors

Bamford, A. (2023). *JCB has manufactured over 50 prototypes powered by Hydrogen*. Capital Equipment News. Retrieved from https://www.crown.co.za/capital-equipment-news/insights/24600-jcb-has-manufactured-over-50-prototypes-powered-by-hydrogen#:~:text=A%20team%20of%20150%20engineers,at%20JCB's%20UK%20engine%20plant

Bakhsh, N. (2022). *IMO to develop safety guidelines for ammonia and hydrogen.* Lloyd's List. Retrieved from https://lloydslist.maritimeintelligence.informa.com/LL1142303/IMO-to-develop-safety-guidelines-for-ammonia-and-hydrogen

Blackmore, L. (2023). *LR issues world's first rules for hydrogen fuel*. Lloyds Register. Retrieved from https://www.lr.org/en/knowledge/horizons/june-2023/lr-issues-worlds-first-rules-for-hydrogen-fuel

Christensen, A. (2020). *Assessment of hydrogen production costs from electrolysis: United States and Europe*. International Council on Clean Transportation. Retrieved from https://theicct.org/sites/default/files/publications/final_icct2020_assessment_of%20_hydrogen_production_costs%20v2.pdf

Carlisle, D. P., Feetham, P. M., Wright, M. J., & Teagle, D. A. H. (2023). Public response to decarbonisation through alternative shipping fuels. *Environment, Development and Sustainability.* https://doi.org/10.1007/s10668-023-03499-0

DNV. (2021). *Handbook for hydrogen-fuelled vessels*. Retrieved from https://www.dnv.com/maritime/publications/handbook-for-hydrogen-fuelled-vessels-download.html

Depken, J., Dyck, A., Roß, L., Ehlers, S. (2022). Safety considerations of hydrogen application in shipping in comparison to LNG. *Energies, 15*(9), 3250. https://doi.org/10.3390/en15093250

Dincer, I., & Acar, C. (2017). Innovation in hydrogen production. *International Journal of Hydrogen Energy, 42*(22), 14843-14864. https://doi.org/10.1016/j.ijhydene.2017.04.107

ENR. (2021). *Rules of Safety for ships using Hydrogen as a Fuel, Technical Standard ENR 14002:2021*. Retrieved from http://www.enrstandards.org/it/files/ENR_14002_31012023.pdf

EU. (2018). *Perspectives for the use of hydrogen as fuel in Inland shipping: A feasibility study*. MariGreen. Retrieved from https://www.dst-org.de/wp-content/uploads/2018/11/Hydrogen-Feasibility-Study-MariGreen.pdf

Fahnestock, J., & Bingham, C. (2021). *Mapping of zero emission pilots and demonstration projects*. The Global Maritime Forum. Retrieved from https://www.globalmaritimeforum.org/content/2021/03/Mapping-of-Zero-Emission-Pilots-and-Demonstration-Projects-Second-edition.pdf

Falfari, S., Cazzoli, G., Mariani, V., & Bianchi, G. M. (2023). Hydrogen application as a fuel in internal combustion engines. *Energies, 16*(6), 2545. https://doi.org/10.3390/en16062545

Gnanasekar, P., Eswaran, M. K., Palanichamy, G., Ng, T. K., Schwingenschlögl, U., Ooi, B. S., & Kulandaivel, J. (2021). Sustained solar-powered electrocatalytic H_2 production by seawater splitting using two-dimensional vanadium disulfide. *ACS Sustainable Chemistry & Engineering, 9*(25), 8572-8580. https://doi.org/10.1021/acssuschemeng.1c01909

Hoecke, L.V., Laffineur, L., Campe, R., Perreault, P., Verbruggen, S. W., & Lenaerts, S. (2021). Challenges in the use of hydrogen for maritime applications. *Energy & Environmental Science, 14*, 815-843. https://doi.org/10.1039/d0ee01545h

IMO. (2018a). *Resolution MEPC.304 (72).* Retrieved from https://unfccc.int/sites/default/files/resource/250_IMO%20submission_Talanoa%20Dialogue_April%202018.pdf

IMO. (2018b). *IMO action to reduce greenhouse gas emissions from international shipping*. Retrieved from https://www.imo.org/en/MediaCentre/HotTopics/pages/reducing-greenhouse-gas-emissions-from-ships.aspx

IMO. (2023). *Progress on safety guidelines for hydrogen- and ammonia-fuelled ships*. Retrieved from https://www.imo.org/en/MediaCentre/Pages/WhatsNew-1968.aspx

IRENA. (2022). *Innovation trends in electrolysers for hydrogen production*. Patent insight report. Retrieved from https://www.irena.org/publications/2022/May/Innovation-Trends-in-Electrolysers-for-Hydrogen-Production

Koundal, A. (2023). *Wartsila working on engine, power plant concept for pure hydrogen operations by 2025*. Economic Times. Retrieved from https://energy.economictimes.indiatimes.com/news/renewable/wartsila-working-on-engine-power-plant-concept-for-pure-hydrogen-operations-by-2025/98512467

Li, H., Cao, X., Liu, Y., Shao, Y., Nan, Z., Teng, L., Peng, W., & Bian, J. (2022). Safety of hydrogen storage and transportation: An overview on mechanisms, techniques, and challenges. *Energy Reports, 8*, 6258-6269. https://doi.org/10.1016/j.egyr.2022.04.067

Mann, M. K., & Spath, P. L. (2004). *Life cycle assessment of renewable hydrogen production via Wind/Electrolysis*. Milestone Completion Report, NREL, United States. https://doi.org/10.2172/15006927

Marine and Offshore. (2021). *Client corner: 6 Questions about Hydrogen as a fuel*. Retrieved from https://marine-offshore.bureauveritas.com/magazine/client-corner-6-questions-about-hydrogen-fuel

Marine Services NORD. (n.d). *Hydrogen Storage on a ship*. Retrieved from https://marine-service-noord.com/en/products/alternative-fuels-and-technologies/hydrogen/hydrogen-storage-on-a-ship

Marine Executive. (2019). *Hydrogen fuel cells destined for France and Norway*. The Maritime Executive. Retrieved from https://maritime-executive.com/article/hydrogen-fuel-cell-vessels-destined-for-france-and-norway

Matthé, J., Jain, P., & Pierre, J. (2022). *Hydrogen in maritime: Opportunities and challenges, WSP*. Retrieved from https://www.wsp.com/-/media/insights/global/documents/wsp---hydrogen-in-maritime-opportunities-and-challenges.pdf

Melideo, D., & Desideri, U. (2024). The use of hydrogen as alternative fuel for ship propulsion: A case study of full and partial retrofitting of roll-on/roll-off vessels for short distance routes. *International Journal of Hydrogen Energy, 50*, 1045-1055. https://doi.org/10.1016/j.ijhydene.2023.10.142

Nikolaidis, P., & Poullikkas, A. (2017). A comparative overview of hydrogen production processes. *Renewable Sustainable Energy Review, 67*, 597-611. https://doi.org/10.1016/j.rser.2016.09.044

OECD. (2023). *Climate change: In environment at a glance indicators*. OECD Publishing, Paris. https://doi.org/10.1787/ac4b8b89-en

Office of Energy Efficiency & Renewable Energy. (n.da). *Types of fuel cells*. Hydrogen and Fuel Cell Technologies Office. Retrieved from https://www.energy.gov/eere/fuelcells/types-fuel-cells

Office of Energy Efficiency & Renewable Energy. (n.db). *Comparison of fuel cell technologies*. Hydrogen and Fuel Cell Technologies Office. Retrieved from https://www.energy.gov/eere/fuelcells/comparison-fuel-cell-technologies

Pathak, P. K., Yadav, A. K., & Padmanaban, S. K. (2023). Transition toward emission-free energy systems by 2050: Potential role of hydrogen. *International Journal of Hydrogen Energy, 48*(26), 9921-9927. https://doi.org/10.1016/j.ijhydene.2022.12.058

Reinsch, W. A., & O'Neil, W. (2023). *Hydrogen: The key to decarbonising the global shipping industry*. Centre for Strategic and International Studies. Retrieved from https://www.csis.org/analysis/hydrogen-key-decarbonizing-global-shipping-industry

Seddiek, I. S., Elgohary, M. M., & Ammar, N. R. (2015). The hydrogen-fuelled internal combustion engines for marine applications with a case study. *Brodogradnja, 66*, 23-38.

Shell. (2022). *Shell to start building Europe's largest renewable hydrogen plant*. Shell. Retrieved from https://www.shell.com/media/news-and-media-releases/2022/shell-to-start-building-europes-largest-renewable-hydrogen-plant.html

Shuit, S. H., Tan, K. T., Lee, K. T., & Kamaruddin, A. H. (2009). Oil palm biomass as a sustainable energy source: A Malaysian case study. *Energy, 34*(9), 1225-1235. https://doi.org/10.1016/j.energy.2009.05.008

Snyder, J. (2022). *LH2 carrier completes 9,000-km voyage transporting liquefied hydrogen*. Riviera. Retrieved from https://www.rivieramm.com/news-content-hub/lh2-carrier-completes-9000-km-voyage-transporting-liquefied-hydrogen-70633

Spath, P. L., & Mann, M. K. (2001). *Life cycle assessment of hydrogen production via natural gas steam reforming*. NREL, United States. https://doi.org/10.2172/764485

Wang, Y., Wright, L., & Zhang, P. (2021). Economic feasibility of LNG fuel for trans ocean-going ships: A case study of container ships. *Maritime Technology and Research*, *3*(2), 202-222. https://doi.org/10.33175/mtr.2021.248055

Wang, Q., Zhang, H., Huang, J., & Zhang, P. (2023). The use of alternative fuels for maritime decarbonization: Special marine environmental risks and solutions from an international law perspective. *Frontiers in Marine Science, 9*, 1082453. https://doi.org/10.3389/fmars.2022.1082453

Wärtsilä. (2021). *Wärtsilä and RINA partner with other stakeholders to deliver a viable hydrogen fuel solution to meet IMO 2050 target*. Wärtsilä Corporation. Retrieved from https://www.wartsila.com/media/news/25-11-2021-wartsila-and-rina-partner-with-other-stakeholders-to-deliver-a-viable-hydrogen-fuel-solution-to-meet-imo-2050-target-3013516

Wärtsilä. (2022). *Hydrogen - Fuel for thought in our Q&A*. Wärtsilä. Retrieved from https://www.wartsila.com/insights/article/hydrogen-fuel-for-thought-in-our-q-a

Xing, H., Stuart, C., Spence, S., & Chen, H. (2021). Fuel cell power systems for maritime applications: Progress and perspectives. *Sustainability, 13*(3), 1213. https://doi.org/10.3390/su13031213