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Towards Decarbonization of the Maritime Transport Sector: A Review of Hydrogen as an Alternative Marine Fuel

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ABSTRACT

This review examines the current landscape of hydrogen production technologies, including thermochemical, electrochemical, and biological methods, highlighting their efficiencies, feedstock requirements, and environmental implications. Furthermore, the paper explores the challenges and advancements in hydrogen storage technologies, primarily on compressed gas, liquefied hydrogen, and solid-state storage. Hydrogen technology across industries, from transportation, to grid energy storage and industrial processes are discussed, with a focus on maritime sector applications, showcasing hydrogen's versatility and decarbonization potential. Despite its promise, large-scale hydrogen adoption is constrained by high costs, infrastructure limitations, and energy efficiency concerns. This review aims to provide a foundational understanding for researchers and policymakers to support the advancement of hydrogen as a key component in future energy systems.

1 Introduction

Climate change and environmental degradation are global challenges that transcend national boundaries, necessitating international collaboration and coordinated action. In response to these pressing issues, a significant breakthrough occurred in 2015 when the Paris Agreement, a legally binding international treaty aimed at substantially cutting greenhouse gas (GHG) emissions was adopted [1]. The agreement set long-term goals to limit global temperature rise to well below 2 °C above pre-industrial levels, with efforts to further restrict it to 1.5 °C, acknowledging that this would greatly mitigate climate risks and impacts [2]. Building on this commitment, the European Commission introduced the European Green Deal, aiming to modernize the EU economy while ensuring net-zero GHG emissions by 2050. A series of proposals have been put forward to align EU climate, energy, transport, and taxation policies with the goal of reducing net GHG emissions by at least 55% by 2030, compared to 1990 levels [3]. Carbon pricing has also been expanded to include the maritime sector, in addition to aviation, within the EU [4]. In alignment with the Paris Agreement, the International Maritime Organization (IMO) has developed its own GHG reduction strategy for global shipping. Its primary objective is to achieve 40% cut in total emissions by 2030 and 70% cut in total emissions by 2040 compared to 2008 and achieve carbon neutrality by the end of the century [5].

Additionally, the target for gradual reduction of the annual GHG emissions caused by burning fossil fuels onboard ships has been established to promote the uptake of renewable and low-carbon fuels. According to the International Energy Agency, the global shipping industry consumed 8.7 exajoules of energy in 2021, all of which came from burning fossil fuels [6]. Today, the share of renewable energy in final energy consumption in maritime transportation sector is only 0.2% [7], which is why incorporating renewable energy sources in maritime transport sector represents an enormous potential for reducing CO_2 emissions and achieving climate goals.

Literature suggests that usage of fuels such as natural gas, biodiesel, methanol and propane can reduce emissions to varying degrees compared to conventional liquid hydrocarbon fuels [8], [9]. Liquefied natural gas (LNG) is often considered a transition fuel due to its lower carbon content compared to heavy fuel oil (HFO). Although LNG emits less CO_2, its use is accompanied by methane slip, a potent GHG that undermines the environmental benefits of using LNG [10]. Biofuels, derived from biomass, offer a renewable energy option for maritime applications. Fuels such as hydro-treated vegetable oil and fatty acid methyl esters have shown potential for reducing GHG emissions by up to 84% [11]. Methanol can also be derived from renewable energy sources, including CO_2 capture, industrial and municipal waste, or biomass, which significantly lowers GHG emissions [12]. Additionally, gas fuels like propane produce fewer emissions compared to heavy fuel oil, eliminating SO_x emissions due to the absence of sulfur, reducing NO_x emissions by 90% and cutting particulate matter and CO_2 emissions by 30% [13].

Recent studies suggest that while LNG, methanol and propane may provide some immediate reductions in emissions, those fuels cannot meet the long-term decarbonization targets without significant technological improvements. Regarding biofuels, the scalability remains a concern due to feedstock availability and competition with other industries such as agriculture. For those reasons, the greatest potential for reducing GHG emissions lies in the advancement of carbon-free fuels [13-15]. On this point, hydrogen is a promising alternative fuel [14], particularly because of its potential to reduce carbon emissions by providing a sustainable energy source.

Technologies such as fuel cells allow for the energy production with zero emissions, using hydrogen as the fuel and producing water vapor as the only byproduct, making it an environmentally friendly alternative to fossil fuels. It has a high energy density, approximately three times that of gasoline, which allows for achieving high efficiencies of various hydrogen applications, including transportation, industrial processes, and power generation. Additionally, it can be produced using renewable energy sources through electrolysis, creating a pathway for a green hydrogen economy. Its versatility allows for different storage and transportation methods, such as compression, liquefaction, or solid-state storage, and it offers rapid refueling times compared to battery-electric alternatives [13, 17]. By integrating hydrogen into energy systems, dependence on fossil fuels can be reduced, contributing to a more sustainable future. At present, almost all hydrogen on the market is produced from fossil fuels [15]. However, there are several challenges associated with hydrogen as a fuel. Hydrogen production is energy-intensive so the cost of production is high, particularly if systems which use renewable energy sources are used and this remains a significant barrier to widespread adoption [16]. Storage and transportation pose further difficulties due to hydrogen's low volumetric energy density, requiring high-pressure tanks, cryogenic liquefaction, or advanced storage materials [17]. The EU is currently working to create the infrastructure to deploy hydrogen refueling infrastructure along the EU territory [18], however at present, immediate hydrogen accessibility is still limited and demands further investment. Finally, due to hydrogen's flammability and tendency to leak because of its small molecular size, safety concerns are to be resolved [19]. The hydrogen economy is still in its early stages, and large-scale adoption depends on government policies, technological advancements, and investment in infrastructure [23, 24].

This paper is intended for a broad readership and aims to systematically present the latest insights, technologies, and research related to hydrogen use in maritime applications, focusing on the last 5 years. The primary motivation for examining hydrogen fuel technology lies in its immense potential to eliminate CO_2 emissions entirely and transition from fossil fuels to renewable energy sources. The following sections provide an overview of the latest methods for hydrogen production, storage, and application as a fuel. Lastly, the paper explores recent advancements in maritime energy systems that incorporate hydrogen as a fuel source.

2 Hydrogen Production Technologies

Literature describes several different hydrogen production techniques, each with distinct benefits, and drawbacks. The main hydrogen production methods include steam methane reforming, electrolysis, biomass gasification, and photoelectrochemical water splitting [25, 26]. This section first provides a detailed explanation of the main hydrogen production methods, followed by a discussion on the classification of hydrogen using color coding, which reflects the environmental impact of each production process. Hydrogen production methods which can be applied both onshore and offshore are reviewed.

2.1 Steam Methane Reforming

Steam methane reforming (SMR) is a catalytic reaction, usually between methane (or other light hydrocarbons) and steam, producing mainly hydrogen, carbon monoxide, and carbon dioxide [27, 28]. The flowchart of a conventional SMR process is showed in Figure 1.

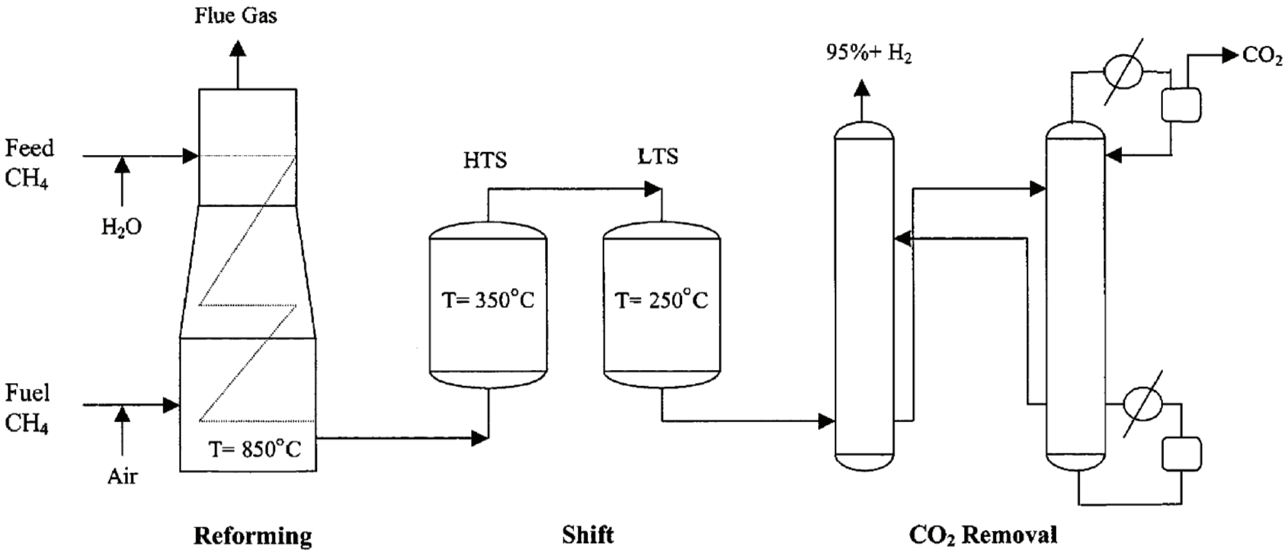

Figure 1 Flowchart of a conventional SMR process [20]

The first step of the SMR process can be described with the following two chemical reactions:

1. Methane reforming reaction:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad \Delta H^0_{298} = 206.2 \text{ kJ/mol} \qquad (1)$$

2. Complete methane reforming:

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2 \qquad \Delta H^0_{298} = 165 \text{ kJ/mol} \qquad (2)$$

The methane and steam react in the reformer furnace to form hydrogen and carbon monoxide. Since these are highly endothermic reactions, additional heat needs to be supplied which can be done by burning supplemental natural gas. The reactions occur at temperatures 800–1000°C and pressures of 14–20 bar over a nickel-based catalyst. The gas mixture (synthesis gas) exiting the reformer contains approximately 76%(mol) hydrogen, 13% methane, 12% carbon monoxide, and 10% carbon dioxide (on a dry basis).

The next stage in the SMR process is the water-gas shift reaction, which takes place in a separate reactor to further increase hydrogen yield:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H^0_{298} = -41.2 \text{ kJ/mol} \qquad (3)$$

This is a mildly exothermic reaction, occurring at temperatures 300–400°C, favoring higher hydrogen production however, some carbon monoxide remains in the gas mixture, which can be further reduced when high-purity hydrogen is required. To purify hydrogen from the synthesis gas, pressure swing adsorption (PSA) technology is commonly used where synthesis gas cyclically passes through an adsorbent material that selectively captures impurities like CO_2 and CO while allowing hydrogen to pass through [21]. The PSA can enable hydrogen purities of up to 99%, making it essential for applications like fuel cells and industrial hydrogen supply. The residual gas, which contains the removed impurities is often recycled or used as fuel for the reformer. This is the predominant method for industrial hydrogen production, contributing to the majority of global hydrogen supply. While it is a well-established and cost-effective process, it depends on fossil fuels, resulting in substantial carbon emissions that hinder its long-term sustainability [22].

2.2 Electrolysis

Electrolysis is the process of breaking down water molecules into hydrogen and oxygen gases using an electric current. When electricity passes through an electrolyte solution between two electrodes, hydrogen is generated at the cathode through the reduction of water molecules, while oxygen forms at the anode through oxidation [23]. Common electrolytes include potassium hydroxide (KOH) or sulfuric acid (H_2SO_4) dissolved in water. When powered by renewable energy sources such as solar, wind, or hydroelectric power, electrolysis provides a carbon-neutral and sustainable method for hydrogen production, making it an environmentally friendly energy solution.

Based on the splitting mechanism and operating conditions, water electrolysis can be classified into three main types: alkaline electrolysis, proton-exchange membrane (PEM) electrolysis, and solid oxide electrolysis (SOE) [24] which are described in more detail below.

Alkaline water electrolysis process, schematically showed in Figure 2 implies the reduction of two molecules of an alkaline solution (KOH/NaOH) at the cathode, producing one molecule of hydrogen and two hydroxyl ions (OH^-) [25].

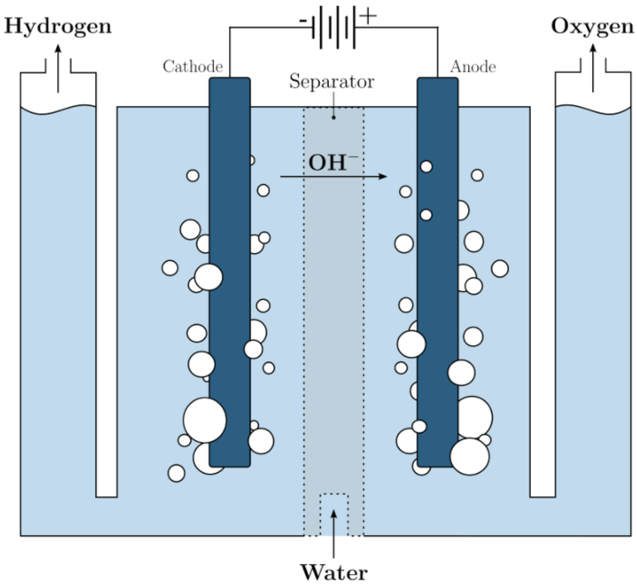

Figure 2 Schematical representation of alkaline water electrolysis process [24]

The hydrogen gas is released from the cathode surface, while the hydroxyl ions migrate through a porous diaphragm to the anode under the influence of an electric field. At the anode, these hydroxyl ions discharge to form half a molecule of oxygen and one molecule of water, with the oxygen gas recombining at the electrode surface and escaping. The process is typically conducted at temperatures up to 80 °C, using an aqueous alkaline solution containing 30% potassium hydroxide (KOH) as the electrolyte. An ion exchange membrane separates the cathode and anode, ensuring that the produced hydrogen and oxygen gases are stored separately for further use.

Solid oxide electrolysis is a process which utilizes a solid oxide electrolyte to split water into hydrogen and oxygen at high temperatures (500-1000 °C). On a schematic presentation of the solid oxide electrolysis, showed in Figure 3 water is supplied in the form of steam to the cathode side of the electrolyzer where steam molecules undergo electroreduction, forming hydrogen gas and oxygen ions (O^{2-}).

The generated oxygen ions move through the solid oxide electrolyte towards the anode where they release electrons and combine to form molecular oxygen gas [25]. Because the process operates at high temperatures, the electrical energy required for water splitting is reduced compared to low-temperature electrolysis however, material degradation due to high-temperature operation, high total energy consumption (thermal and electrical) and slow adoption due to high capital costs make its large-scale commercialization challenging [26]. The reduced amount of electrical energy is accounted for by the thermal energy needed for steam production.

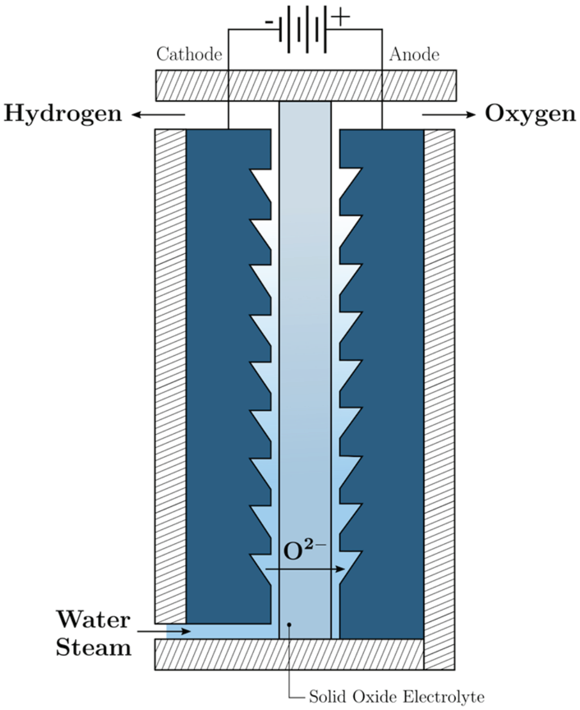

Figure 3 Schematical representation of solid oxide water electrolysis process [24]

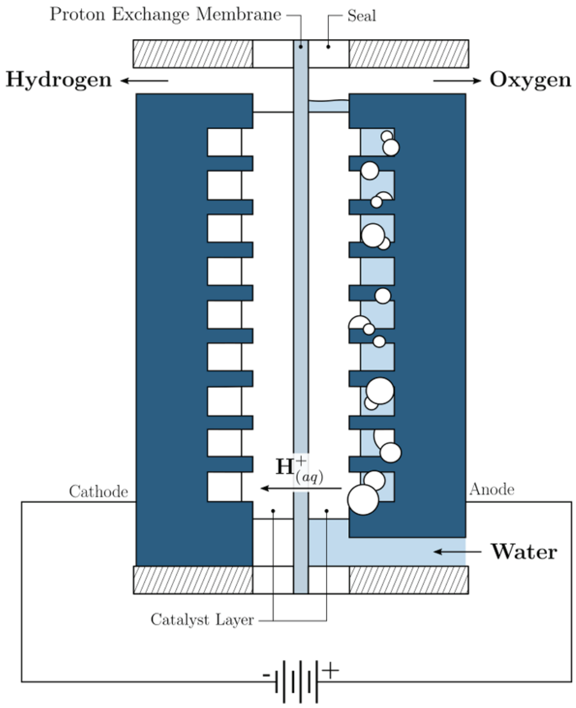

Figure 4 Schematical representation of proton exchange membrane electrolysis process [24]

Proton exchange membrane (PEM) electrolysis, schematically showed in Figure 4 is a type of water electrolysis where the water is split into hydrogen and oxygen using a proton-conducting membrane as the electrolyte [25].

This process occurs in an electrolyzer which consists of the anode and the cathode separated by a proton exchange membrane. At the anode, water undergoes an oxidation reaction, splitting into oxygen (O_2), hydrogen protons (H^+) and electrons (e^-). The oxygen gas is released as a byproduct, and the generated hydrogen protons travel through the proton-conducting membrane to the cathode. The electrons generated at the anode move through an external electrical circuit, providing the driving force for the reaction. At the cathode, protons combine with electrons to form hydrogen gas. This process operates at temperatures 60-80 °C. It can efficiently provide high hydrogen purity in short amount of time. It is generally suitable for renewable energy integration however, the materials used as catalysts such as platinum and iridium significantly increase its cost. Additionally, membrane degradation over time can degrade its efficiency and shorten its lifespan. Finally, it requires significant electrical energy for water splitting. Regardless of the disadvantages of this electrolysis method, the possibility of powering the PEM electrolysis using only renewable energy sources makes this a promising solution for clean energy production [27].

2.3 Biomass Gasification

Another approach to hydrogen production is biomass gasification. Similar to steam methane reforming, this process involves the incomplete combustion of biomass feedstocks such as agricultural residues, wood chips, or municipal solid waste, resulting in the formation of carbon monoxide. Through the water-gas shift reaction (Eq. 3) described earlier in section 2.1, this carbon monoxide is then converted into a synthesis gas composed of hydrogen, carbon monoxide, carbon dioxide, and other gases [28]. The synthesis gas undergoes separation and purification to extract hydrogen for fuel use. Biomass gasification utilizes renewable, carbon-neutral feedstocks, decreasing reliance on fossil fuels and helping to reduce greenhouse gas emissions [29]. The fact that this method uses waste materials, reducing the environmental impact and that it can be integrated with carbon capture technologies to minimize CO_2 emissions make it a renewable and sustainable option for hydrogen production. However, to produce it on a large-scale, the problem of the inconsistent quality of biomass feedstocks needs to be resolved and the efficiency of the biomass gasification process needs to be improved [30].

2.4 Photoelectrochemical Water Splitting

Photoelectrochemical water splitting is a type of electrolysis which utilizes solar energy for hydrogen production. It relies on semiconductor-based photoanodes that absorb sunlight to drive the electrochemical reaction [31]. Upon light absorption, the electrons travel to the cathode, where they reduce protons to produce hydrogen gas, while the oxygen is generated at the anode through the oxidation of water molecule as showed schematically on Figure 5.

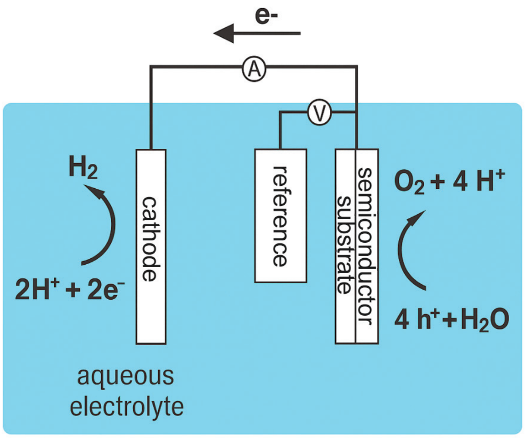

Figure 5 Schematic representation of photoelectrochemical water splitting [32]

The photoanode (a semiconductor material that can absorb sunlight) absorbs sunlight and generates electron-hole pairs. The aqueous electrolyte provides ions for charge transport and the external circuit allows electron flow from the photoanode to the cathode. These photoexcited charge carriers drive the electrochemical splitting of water molecules into hydrogen and oxygen gases at separate electrodes. The main drawbacks of this method for hydrogen production are related to its low efficiency, slow charging and hydrogen and oxygen gas separation however, recently it has gained more attention due to its simplicity, scalability, and cost-effectiveness [32].

Another hydrogen production method which can be found in literature is thermochemical water splitting which requires great amounts of heat energy to break water molecules into hydrogen and oxygen through a series of chemical reactions. This is why nuclear energy is usually used for this process [33]. Operating temperatures range between 500 and 1000°C. Unlike electrolysis, this method does not require electricity, making it an attractive option for producing hydrogen on a large scale.

Hydrogen production using nuclear energy is characterized by potentially very high efficiency (up to 80% in case of high-temperature electrolysis such as solid oxide electrolysis) [33]. However, as with other nuclear technologies, safety, waste management and public perception are the main concerns associated with this method. Additionally, the technology is still in early stages of development with uncertain feasibility.

The efficiencies, advantages, disadvantages and challenges of each main hydrogen production methods are systematically reviewed in Table 1. The efficiency of a hydrogen production method is the ratio of the available energy within the produced amount of hydrogen and the total consumed energy for its pr*oduction.*

Table 1 Comparison of the most common hydrogen production methods

Technology	Efficiency	Advantages	Disadvantages	Challenges	Ref.
Steam methane reforming (SMR)	65–75%	– Most widely used and cost-effective method. – Established infrastructure for production and distribution.	– High CO_2 emissions (unless combined with CCUS). – Relies on fossil fuel (natural gas).	– Requires large-scale carbon capture and storage for emissions reduction.	[28, 29]
Electrolysis (Alkaline, PEM, SOE)	60–70% (alkaline and PEM), 80–90% (SOE)	– Can produce green hydrogen if powered by renewable energy. – Zero direct CO_2 emissions. – Can be implemented on greater scale.	– High electricity consumption. – Expensive compared to fossil fuel-based methods.	– Reducing the cost of electrolyzers and renewable energy infrastructure. – Material degradation in PEM and SOE cells.	[34, 36]
Biomass gasification	35–55%	– Uses renewable organic waste for hydrogen production. – Can achieve net-zero or negative CO_2 emissions if carbon capture is utilized.	– Lower efficiency compared to SMR and electrolysis. – Requires complex purifying processes to remove impurities.	– Inconsistent feedstock quality. – Reducing capital costs for large-scale plants.	[37, 39]
Photoelectrochemical (PEC) water splitting	5–20%	– Directly uses solar energy to convert sunlight into hydrogen without needing electricity. – Environmentally friendly, producing zero CO_2.	– Lowest efficiency method. – Uses semiconductors, which degrade over time.	– Increasing the efficiency and lowering the cost of photoelectrodes.	[32]
Nuclear power hydrogen production (high temperature electrolysis, thermochemical water splitting)	45–55% (thermochemical), 70 – 80% (high temperature electrolysis)	– Provides continuous, low-carbon hydrogen production. – Can reduce electricity demand (if high-temperature electrolysis is used).	– High capital and infrastructure costs. – Associated with public concerns regarding nuclear safety and waste disposal.	– Integration with existing nuclear reactors and scaling up for commercial use.	[41, 42]

2.5 Classification of Hydrogen Origin Through Color Coding

Each of the discussed hydrogen production method contributes uniquely to the development of sustainable hydrogen technologies. The steam methane reforming method is the most economical but has high CO_2 emissions unless combined with carbon capture, utilization and storage. Electrolysis can be clean and it is scalable, but expensive and requires large amounts of electricity. Biomass gasification can be carbon-neutral if combined with carbon capture, utilization and storage, but its efficiency and feedstock quality inconsistency are major drawbacks of this method. Photoelectrochemical water splitting is a promising but low-efficiency technology still in early stages of development. Nuclear hydrogen offers stable, large-scale production, but safety and cost remain challenges.

A common way of declaring the origin of hydrogen in a sense of describing the environmental impact of the method used for production is through color-coding. Based on the reviewed research papers, grey, green, and blue hydrogen are the most commonly mentioned types [34].

Grey hydrogen is produced through the process of SMR, without carbon capture, utilization, and storage. In early stages of development hydrogen energy systems technology, its use was justified so as for the technology to gain a momentum by using grey hydrogen as a transitional fuel as a way of stimulating the production of hydrogen-powered engines for faster moving towards a cleaner energy future. This ensured a convenient and affordable way of producing hydrogen [35]. However, in 2025. it is still the most common hydrogen on the market and since it is also produced from fossil fuels and

Table 2 Grey, blue and green hydrogen comparison

Color	Advantages	Disadvantages
Grey Hydrogen	– Lowest cost hydrogen production method. – Established infrastructure and supply chains. – Large-scale production is readily available.	– High CO_2 emissions, contributing to climate change. Depends on fossil fuels (natural gas). – Not a sustainable long-term solution.
Blue Hydrogen	– Lower CO_2 emissions compared to grey hydrogen. – Uses existing SMR infrastructure with added carbon capture. – Provides a transition solution before green hydrogen becomes cost-competitive.	– Still relies on natural gas, a non-renewable resource. – Carbon capture is not 100% efficient, leading to some emissions. – High cost of CCUS technology increases production expenses.
Green Hydrogen	– 100% clean and sustainable (zero CO_2 emissions). – Uses renewable energy sources like solar, wind, and hydro. – Supports global carbon neutrality goals.	– Expensive due to high costs of electrolyzers and renewable energy. – Requires large-scale renewable energy capacity. – Storage and transportation remain challenging.

without carbon capture and storage technology, grey hydrogen is the most carbon-intensive of the three types, as it produces significant amounts of GHG emissions during the production process. Due to the significant emissions associated with grey hydrogen, in terms of ecology and environment protection, it is generally considered to be the least desirable of the three types.

Blue hydrogen is also derived from steam methane reforming, but with the incorporation of carbon capture, utilization, and storage technology. Storing the CO_2 causes less emissions compared to conventional power production through burning of fossil fuels. However, levels of CO_2 capture in existing blue hydrogen plants vary from 50% to 83%, which is far below the industry goal of 95% of captured and stored CO_2 [35]. Additionally, such processes are powered by natural gas resulting in methane emissions, which negatively impact the global warming much stronger than CO_2 emissions. The most significant advantage of blue hydrogen over green hydrogen is that it can be produced at a lower cost, as the cost of natural gas is lower than the cost associated with renewable energy sources [27, 28].

Green hydrogen is generated via the process of water electrolysis using renewable energy sources such as wind, solar, and hydro power. It is crucial that the energy for electrolysis is produced using the renewable energy sources as only then the produced hydrogen can classify as green. This is the cleanest form of hydrogen since it does not contribute to GHG emissions, which makes it ideal for decarbonization and achieving climate goals [17, 33]. Although the high production costs lower the feasibility of green hydrogen, with cost reductions and advancements in hydrogen transport infrastructure, green hydrogen has a potential of replacing fossil fuels in industries, transport, and power generation [26]. Additional comparison of the three types of hydrogen is presented in Table 2.

Other colors include turquoise hydrogen which is produced through pyrolysis of methane to solid carbon and hydrogen gas; red hydrogen, produced through thermochemical processes such as thermochemical water splitting; pink hydrogen, produced through electrolysis using nuclear power generated energy; white, naturally occurring geological hydrogen; black, produced from black coal or lignite (brown coal) through a 'gasification' process and purple hydrogen which is produced through thermochemical processes using nuclear energy. In different literature however, different categorization can be found [17, 45, 46].

Ultimately, the choice of which type of hydrogen will be used depends on several factors including cost, availability, and environmental impact, but in order to reduce the reliance on fossil fuels and preserve the environment and climate, a shift towards green hydrogen production is necessary.

3 Hydrogen Storage and Transport Technologies

3.1 Hydrogen Storage Methods

Hydrogen fuel, a lightweight gas with high energy density presents distinct challenges for storage and distribution, necessitating specialized infrastructure and technologies to maintain safety, efficiency, and reliability of hydrogen systems. The main storage methods include compression of hydrogen in gaseous state, liquefaction of hydrogen and incorporation within metal hydrides through hydrogen atom bonding [47, 48]. In this section, benefits and drawbacks of each are discussed in detail.

The process of storing hydrogen in a gaseous state is relatively simple since it mainly involves compressing hydrogen at high pressures. The reason for that is to increase its energy density while maintaining its gaseous state because hydrogen has a low volumetric energy density compared to conventional fuels. Typical compression pressures are 350-700 bar but recently, working pressures of 900 bar were achieved in low-temperature-high-pressure composite hydrogen storages [36]. Unlike the other storage methods, it does not utilize refrigeration units or heavy hydrogen carrying materials [37]. Other advantages include its simple infrastructure, rapid refueling capabilities, and ease of handling which are the reasons for why it has been in application for decades. However, because of its very low density, to store 1 kg of hydrogen at 20 °C and 1 bar, a volume of 12 m^3 would be needed and this is the reason why gaseous hydrogen is compressed to such high pressures. Storing hydrogen as a gas requires high-strength pressure vessels to ensure safety and efficiency, thus the primary challenges associated with gaseous hydrogen storage include material fatigue, hydrogen embrittlement, and the risk of leaks [38]. Additionally, high pressures, small hydrogen molecular size and high hydrogen diffusivity necessitate advanced sealing technologies and reinforced tank designs to withstand the extreme stress exerted by the compressed gas and reduce leakage which can be a limiting factor for implementation such storages in systems where size and weight are crucial such as on ships [39]. Finally, even when stored at pressures 350 bar to 700 bar, hydrogen density ranges from 23.3 kg/m^3 to 39.3 kg/m^3, which still is 2 to 3 times lower than the density of liquid hydrogen.

Liquid hydrogen storage involves cooling hydrogen to -253 °C (20.4 K) at pressures 1-10 bar to achieve a high-density state suitable for long-term storage and transport. A refrigeration unit is required for such processes, which increases the cost and the complexity of such systems. Compared to compressed gaseous hydrogen, liquid hydrogen has higher energy density (~8.5 MJ/L), making it a preferred option for applications requiring large-scale storage and long-distance transportation [53, 54]. The compactness, i.e., lower size and weight and higher capacity compared to compressed hydrogen gas makes liquid hydrogen suitable for large-scale applications such as for ship propulsion systems. Additionally, storing hydrogen in liquid state requires significantly lower pressures compared to compressed gas hydrogen storage, reducing stress on storage tanks. However, the liquefaction process is energy-intensive, consuming approximately 30–40% of hydrogen's energy content and about 10% of hydrogen is lost during compression [17]. Despite operating the refrigeration unit, part of the hydrogen continuously evaporates due to heat gains, requiring storage venting and leading to hydrogen loss over time [40]. The storage tanks must have multi-layer insulation to minimize heat transfer and prevent excessive hydrogen loss. Due to the different contraction coefficient of storage materials under low temperatures, high stress can build upon tanks made of hybrid materials, causing structural failure of the tank which could lead to massive leakages of flam-

Table 3 Comparison of the advantages, disadvantages, working parameters and energy densities of storing hydrogen as a gas, liquid and within metal hydrides

Method	Advantages	Disadvantages	Working parameters	Energy density	Ref.
Compressed hydrogen gas	– Well-established storage method – Relatively short refilling time – Suitable for refueling stations, industrial processes, and backup power systems	– Lower hydrogen density compared to liquid hydrogen (23.3 kg/m^3 at 350 bar and 39.9 kg/m^3 at 700 bar) – Requires bulky and heavy storage tanks, limiting applications with space/weight constraints.	40 to 85 °C 350-700 bar	4.97 MJ/l (at 700 bar)	[60-62]
Liquid hydrogen	– High density (70 kg/m^3) – Enables compact storages – Stored at ambient pressure – Reduced tank weight – Easier transportation and refueling	– Energy-intensive refrigeration needed for liquefaction and storage – Evaporation and leakage losses at cryogenic temperatures – Material stress due to operating at low temperatures	-253 °C 1-10 bar	8.5 MJ/l	[63-66]
Material-based (metal hydrides) storage	– Hydrogen stored at ambient temperature and pressure – Relatively high storage density (40–100 kg/m^3)	– High weight due to metal hydrides – High cost – Low hydrogen release rate – Longer refueling time compared to liquid hydrogen – Risk of explosion due to heat generation during charging	25-120 °C 1-10 bar	1.5-2.0 MJ/l	[67-69]

mable hydrogen fuel and thus pose severe safety concerns. For that reason, specialized cryogenic materials need to be used for tanks and pipelines, resilient to brittle fracture [19].

Finally, hydrogen can be stored within solid materials, such as metal hydrides, compounds that can absorb and release hydrogen under certain operating conditions (20-400 °C and 10-100 bar) [41]. Various metals and alloys, such as $LaNi_5H_6$ and Mg_2NiH_4 have been studied for their ability to reversibly store hydrogen. However, due to the high atomic weight of metal components, hydrogen capacity of such storages is only 1.4% of the total storage mass [42]. Lighter metal hydrides, such as lithium hydride (LiH), can increase hydrogen storage capacity to 12.6%, but its' high hydrogen release temperature of around 720 °C makes it impractical for most mobile applications [43]. A promising alternative to conventional metal hydrides is the use of hybrid materials combining metal-organic frameworks (MOFs) with hydride-forming metal nanoparticles [44]. These materials enable improved hydrogen charge and release rates. The metal-organic frameworks enhance hydrogen storage stability, lower desorption temperatures, and improve moisture resistance compared to conventional metal hydrides [42]. The main drawbacks of this method include the relatively high weight and cost of the system, a longer charging time compared to liquid hydrogen, and heat generation during hydrogen molecule charging, which increases the risk of explosion [37]. A systematic comparison of the advantages, disadvantages, working parameters and energy densities of the three different hydrogen storing methods is given in Table 3.

3.2 Hydrogen Pressure Vessel Types

Hydrogen pressure vessels are a widely used technology for storing gaseous hydrogen due to their ability to offer fast refueling and relatively simple infrastructure requirements [45].

Common types of pressure vessels include cylindrical and spherical designs. Cylindrical vessels are more cost-effective than spherical ones because they are easier to manufacture and can be stored and transported more efficiently. However, a drawback linked to cylindrical vessels is the presence of weak points at the joints between the shell and the heads, where stress is concentrated. In contrast, spherical vessels distribute stress evenly across their entire surface due to the absence of sharp edges. Additionally, spherical vessels have a higher volume-to-surface area ratio and require only half the wall thickness of cylindrical vessels to achieve the same strength at equal operating pressure, resulting in lower material usage [46].

Hydrogen's small molecular size leads to permeation issues, especially at high pressures. To address this, multi-layered vessels are preferred, with composite materials enabling storing hydrogen with high densities [71, 72]. Hydrogen pressure vessels can be classified into 5 types according to the structure of the materials used [20, 50, 73].

Type I pressure vessels are entirely made of metal (usually steel and aluminum alloys). Because of their relatively simple design, Type I vessels are the easiest to manufacture among the four types. These cost-effective vessels can be produced to have large capacities, with the working pressure around 200 bar [47]. However, such vessels are usually heavy, making them less suitable for mobile hydrogen applications [48].

The difference between Type I and Type II pressure vessels is that the cylindrical section of the Type II vessels is wrapped with carbon fiber or glass fiber filament which makes them more resilient to higher operating pressures, typically around 300 bar. Even though these storages are lighter in weight compared to Type I storages, they are heavier than the full composite vessels, and their use is also limited in mobile applications [17].

Whereas the Type II hydrogen pressure vessels are only partially composite-wrapped, the Type III pressure vessels are fully wrapped in composite material, usually carbon fiber, while the liner is made of aluminum alloy. Compared to Type I and II, these vessels are even more resilient to high operating pressures (up to 700 bar). Additionally, they are lighter in weight and more compact which is why their use is more suitable to mobile hydrogen system such as hydrogen-powered vehicles [49]. The cost of Type III vessels is the highest among the commercially available Type I-IV vessels due to their construction materials [50].

The only difference between Type III and IV vessels is that Type IV uses polymeric liner while Type III uses metallic liner. In both Type III and IV storages the thin layer of liner functions to seal the gas in the tank and a thicker outer composite wrap is the main load-bearing component [51]. These are the lightest among the four commercially available hydrogen vessels, with high working pressure capability of up to 700 bar, applicable in mobile systems such as fuel cell electric vehicles [52]. High strength and low density of carbon fibers used for wrapping Type III and IV hydrogen vessels allow higher operating pressures as compared to Types I and II and both vessel weight and wall thickness are significantly lower. However, a challenge associated with these storage types is hydrogen permeation which is why careful pressure cycling management needs to be applied [53].

Regarding the cost of composite hydrogen storage vessels, the processing cost contributes to about half of the total cost. Cost reduction by developing advanced manufacturing techniques is more promising compared to the cost reduction due to materials' price reduction [45].

Type V tanks are composite pressure vessels with no internal polymer liner. Instead, the composite material acts as both the gas barrier and the load-bearing structure. This design eliminates the need for strain compatibility between a liner and the composite, potentially improving fatigue performance and enabling a 10–20% weight reduction compared to vessels with liners. Type V tanks rely on the carbon fiber laminate to provide structural properties and prevent gas leakage at high pressures, but achieving this has posed significant engineering challenges that have so far limited commercial application [54], particularly in strict safety-demanding applications like aerospace, automotive and maritime transport sectors. Nevertheless, such storages can potentially achieve high strength-to-weight ratios and withstand pressures up to 700 bar.

3.3 Liquid Hydrogen Storages

Storing liquid hydrogen requires highly insulated storage vessels to minimize heat gains and hydrogen losses due to evaporation. These storage tanks use vacuum insulation, with an inner pressure vessel enclosed by an external protective jacket, enhanced with powder structure perlite, aerogels, or multi-layer insulation to attain zero-boil-off liquid hydrogen storage [55]. Both passive and active technologies for reducing heat transfer to hydrogen and hydrogen leaks are investigated in literature [56]. Example of passive methods are variable density multi-layer insulation which implies placing the higher-density layers closer to the warmer exterior and lower-density layers near the cold interior, and self-evaporation vapor-cooled shield where the hydrogen vapor which arises due to the unavoidable heat gains from environment is sent to circulate around an insulated shield to absorb the heat before escaping or being reliquified [57]. Both methods significantly reduce heat flux and improve storage efficiency compared to traditional storage insulations. Examples of active technologies for reducing hydrogen loss and achieving zero boil-off are turbo-Brayton cryocoolers and Stirling pulse tube cryocoolers which are used for re-liquifying vapor hydrogen [82, 83].

3.4 Material Based Hydrogen Storages

Material based hydrogen storages typically require additional components which have the ability to adsorb hydrogen molecules. In literature, metal hydrides are the most commonly used and investigated materials for material-based hydrogen storage applications [58]. There are three primary types of metal hydride reactors: tubular, disc, and chamber (or tank) reactors [59]. One of the key components in metal hydride reactors is the heat exchanger, which plays a crucial role in ensuring fast reaction kinetics [60]. During hydrogen absorption, an exothermic reaction occurs, generating heat. This can cause a temperature rise, which in turn could slow the reaction rate. To counter this, an efficient cooling mechanism is required. Conversely, hydrogen desorption is an endothermic process, meaning it requires an effective heating system to maintain a high reaction rate. Extensive research has been conducted to enhance heat transfer efficiency in metal hydride reactors for optimal cooling and heating performance during hydrogen adsorption and desorption. Various approaches have been explored, including the integration of fins, metal powders, and metal foams to increase thermal conductivity. Additionally, the use of fluid baths, embedded cooling tubes, and phase change materials has been investigated as potential means to further improve heat transfer efficiency [61].

3.5 Safety Challenges of Compressed Hydrogen Storage on Ships

Storing compressed hydrogen on ships poses potential safety risks. The harsh marine environment can cause fittings and equipment to deteriorate, making them prone to leaks due to corrosion, vibrations, aging, loosening of joints, and collisions. As a result, released hydrogen can form combustible (4–75%) or explosive (18–58%) mixtures in the air [62]. Several researchers have highlighted the critical need for safe hydrogen storage on ships. Soto et al. [62] numerically investigated hydrogen release and dispersion in under-deck compressed hydrogen storages on ships and stated that safe storage remains a challenge. Wang et al. [63] conducted a CFD analysis to investigate hydrogen leakage from a tank, focusing on the impact of roof design, leak size, and ignition point on hydrogen dispersion. Their findings revealed that the majority of the flammable cloud accumulates within a half-meter layer below the ceiling. Based on this, they recommended that regulations should include limits on maximum roof surface area to improve the dissipation of hydrogen clouds. Similar was suggested by Li et al. [64] who stated that storing hydrogen on open decks significantly reduces fire-related risks, it has drawbacks such as exposure to harsh marine conditions and external forces, a higher likelihood of leaks caused by corrosion, and potential negative effects on the ship's stability due to the added weight in elevated positions.

From a logistical standpoint, integrating hydrogen into existing shipping and port operations requires new storage facilities, dedicated pipelines, and bunkering systems [65]. The establishment of a reliable global supply chain for hydrogen remains underdeveloped, with only limited pilot projects currently in place. Furthermore, the scalability of hydrogen refueling operations is uncertain, as existing concepts are designed mainly for ferries and short-sea shipping rather than large transoceanic vessels. This lack of supply chain maturity and global refueling standards represents a significant barrier to widespread deployment.

Presently some classification societies suggest using existing rules for liquid natural gas and compressed

Table 4 An overview of regulations and guidelines issued by the classification societies [70]

Classification society	Document	Year
American Bureau of Shipping (ABS)	Requirements for Hydrogen Fueled Vessel	2023
	Guide for Gas and Other Low-Flashpoint Fuel Ready Vessels	2022
	Guide for Fuel Cell Power Systems for Marine and Offshore Applications	2019
Lloyd’s Register (LR)	Rules and Regulations for the Classification of Ships utilizing Gases or other Low-flashpoint Fuels	2023
	Appendix LR 3 – Requirements for Ships Using Hydrogen as Fuel	2023
Bureau Veritas (BV)	Rules for hydrogen-fuelled ships (NR 678)	2023
	Regulations on fuel cell power systems (NR 547)	2022
Det Norske Veritas (DNV)	Rules Part 6 Chapter 2 Section 3: Fuel Cell Installations	2022
	Handbook for hydrogen-fuelled shipping	2021
The China Classification Society (CCS)	Guidelines for Ships Using Fuel Cell Power Installations	2022
The Korean Register (KR)	Guidance for fuel cell systems on board ships	2022
The Nippon Kaiji Kyokai (ClassNK)	Guidelines for Liquefied Hydrogen Carriers	2017

natural gas as a starting point, with additional hydrogen-specific assessments needed (e.g., material compatibility, hydrogen embrittlement). For compressed hydrogen, rules for compressed natural gas ships given by Det Norske Veritas, DNV are used as a baseline, although these are not directly applicable to hydrogen without modification [66]. The American Society of Mechanical Engineering, ASME B31.12 standard covers hydrogen piping and pipelines and can provide input for maritime applications. Finally, International Organization for Standardization, ISO standards such as ISO/TR 15916 (Safety of hydrogen systems) and others under development are also relevant for usage.

4 Hydrogen Applications in Maritime Sector

Hydrogen has traditionally been used worldwide for petroleum refining, ammonia fertilizer production, and refinement of metals such as nickel, lead, zinc, copper, tungsten and molybdenum [89-91]. However, hydrogen fuel can be used to replace fossil fuels in all fossil fuel applications [67]. This is especially the case in transport and industrial sectors where replacing fossil fuels with clean energy could help in reducing pollutions and achieving climate goals. Other than traditional hydrogen applications, hydrogen can be used for power generation, as a fuel for powering vehicles and for heating. Due to the great potential of replacing fossil fuels in transportation sector which is responsible for around 20% of the total CO_2 emissions [68], in this section main hydrogen utilization technologies and applications in maritime sector are discussed. Hydrogen can be used for electrical power generation by utilizing fuel cells. The produced electricity can be used for driving the electromotor which powers a vehicle. A detailed, up to date review of hydrogen powered ships already completed and under development can be found in [69].

Storing and using of hydrogen as a fuel onboard is presently covered globally by International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code). The code covers design and operation of ships using alternative fuels (including hydrogen). Although it is focused on LNG ships, it serves as a starting point for hydrogen ships, while hydrogen-specific provisions are being developed. It contains detailed prescriptive requirements mainly for LNG, while for hydrogen and other low-flashpoint fuels, the use of the ‘Alternative Design’ approach is mandated, requiring a demonstration that the hydrogen system provides an equivalent or higher safety level compared to conventional fuels. Fuel cells are expected to be included in the IGF Code in the future, with temporary guidelines currently in place. However, no specific IMO work has started to cover hydrogen storage onboard ships [66]. Since prescriptive rules for hydrogen are not yet established, approval follows a risk-based Alternative Design process which entails comprehensive risk assessments to prove equivalent safety compared to conventional oil-fueled ships.

Recognizing the increasing interest in hydrogen as a fuel, multiple classification societies, have issued certain rules and guidelines for the use of hydrogen as a marine fuel and are given in Table 4 [70].

4.1 Fuel Cells

Fuel cells are electrochemical devices that convert the chemical energy of hydrogen directly into electricity through a reaction with oxygen, typically from the air. Compared to traditional combustion-based power generation, hydrogen fuel cells provide several benefits, including improved energy efficiency, lower emissions, and quieter operation due to having only water and heat as the byproducts [71]. The main elements of fuel cells are anode, cathode, electrolyte, catalyst and bipolar plates. The fuel (hydrogen or a gas with high hydrogen content) is supplied to the anode which, if produced using renewable energy sources makes the fuel cells systems that utilize renewable energy sources. The catalyst is needed to split hydrogen into H^+ protons and electrons. The electrons travel from anode to cathode through an external circuit and the H^+ protons travel from the anode to the cathode through electrolyte. The electrolyte is made of an ion conducting material. It separates the two gases and acts as a filter to inhibit direct mixing of the cell reactants and conduct the charged ions created during partial cell reactions. It also does not conduct electrons. The bipolar plates aid in distributing hydrogen and oxygen evenly across the electrodes and they conduct electrons. There are several types of fuel cells technologies which differ mostly in the type of the electrolyte and operating temperatures. This also results in different efficiencies of various fuel cell technologies and different applications. In this section, main fuel cell types are reviewed [79, 97].

4.1.1 Proton Exchange Membrane Fuel Cells

Proton exchange membrane (PEM), also referred to as polymer electrolyte membrane (PEM) fuel cells utilize a solid polymer electrolyte membrane, typically poly-perfluorocarbon sulfonate which conducts hydrogen protons (H^+) and inhibits electron transfer from one electrode to the other. It is typically made of platinum or platinum alloy [72]. The PEM fuel cell is schematically showed in Figure 6.

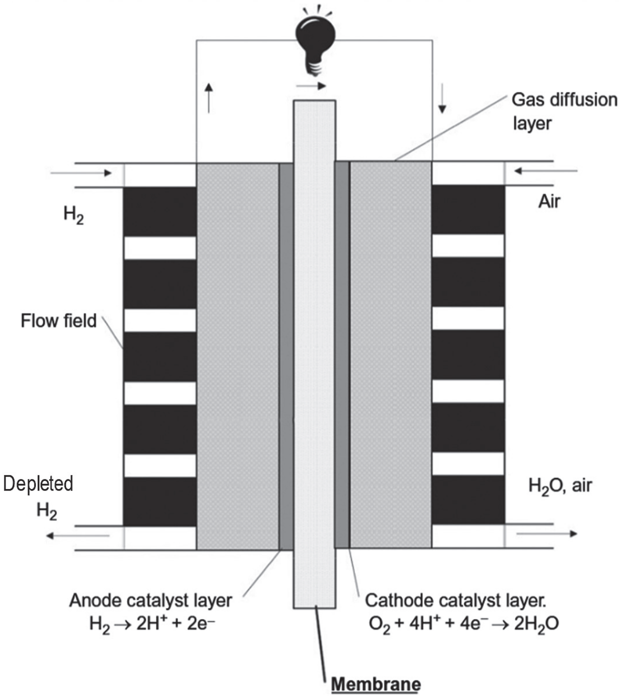

Figure 6 A schematic representation of a proton exchange membrane fuel cell [73]

Hydrogen gas is introduced at the anode, where the catalyst splits the hydrogen molecule into protons and electrons according to:

$$H_2 \rightarrow 2H^+ + 2e^- \tag{4}$$

The generated electrons which are transported across the external circuit allow for splitting the oxygen molecules which are introduced at the cathode, according to:

$$O_2 + 4e^- \rightarrow 2O^{2-} \tag{5}$$

The electrical energy of the transported electrons can be used for powering devices. Finally, the positively charged hydrogen protons are attracted by the negatively charged oxygen ions which react to form a water (vapor) molecule according to:

$$O^{2-} + 2H^+ \rightarrow H_2O \tag{6}$$

which completes the reaction.

The three partial reactions can also be written with only two partial reactions such as on Figure 6.

Some of the advantages of the PEM fuel cells are fast startup, high power density, and fast responsiveness, making them suitable for power generation on vehicles, as well as in stationary applications [34, 99].

4.1.2 Alkaline Fuel Cells

Alkaline fuel cells use an alkaline electrolyte, typically a potassium hydroxide (KOH) solution to transport hydroxide ions (OH^-) between the anode and cathode [74]. Similarly like in PEM, in alkaline fuel cell hydrogen gas is supplied to the anode and split into protons and electrons. The electrons are transferred to the cathode.

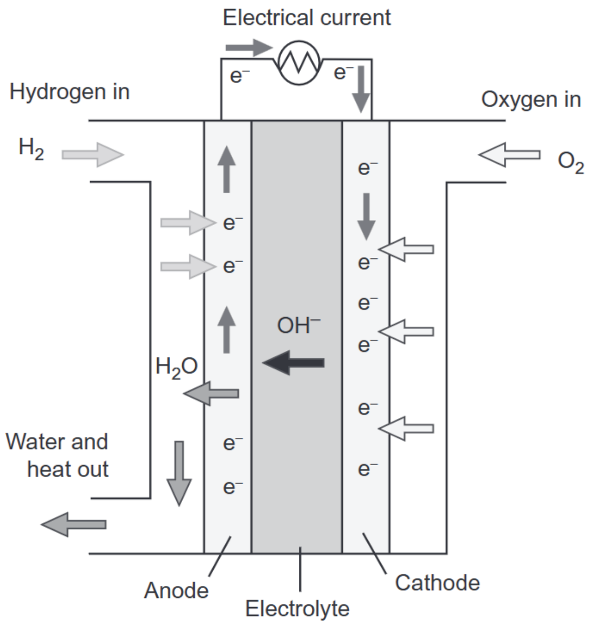

Figure 7 A schematic representation of an alkaline fuel cell [74]

Oxygen is supplied to the cathode and split to negatively charged oxygen ions which here react with water from the potassium hydroxide water solution to form hydroxide ions, as showed in Figure 7.

The hydroxide ions pass through the electrolyte and react with the hydrogen positively charged ions and the anode whereby water is generated as a byproduct. The alkaline fuel cells have been widely used in aerospace and space missions for decades due to their efficiency and reliability. However, they require pure hydrogen and are highly sensitive to CO_2 contamination [79, 96].

4.1.3 Solid Oxide Fuel Cells

These fuel cells, schematically showed in Figure 8 utilize a solid ceramic electrolyte, commonly made from zirconium oxide, ZrO_2 (zirconia), with added yttrium oxide, Y_2O_3, to conduct oxygen ions (O^{2-}) from cathode to anode. However, in order for such electrolytes to conduct oxygen ions, the cell must operate at high temperatures (600–1000 °C) [75].

Unlike the electrolyte in PEM, the electrolyte in solid oxide fuel cells conducts oxygen ions instead of hydrogen ions. Hydrogen gas is supplied to the anode and split into protons and electrons with the aid of a catalyst. The electrons are transferred to the cathode and used for splitting an oxygen molecule to two negatively charged oxygen ions. These negatively charged ions are transferred to the anode through the electrolyte where in reaction with positively charged hydrogen ions water steam is generated and carried away in the excess fuel gas stream. The advantage of solid oxide fuel cells is that other than hydrogen, natural gas and biofuels can be used can be used as fuel as well [76]. The high operating temperatures make them suited for stationary power generation and combined heat and power systems where the high temperature heat could be recovered in steam generator to drive a steam turbine. It is estimated that this way an overall efficiency of 73% could be achieved [77].

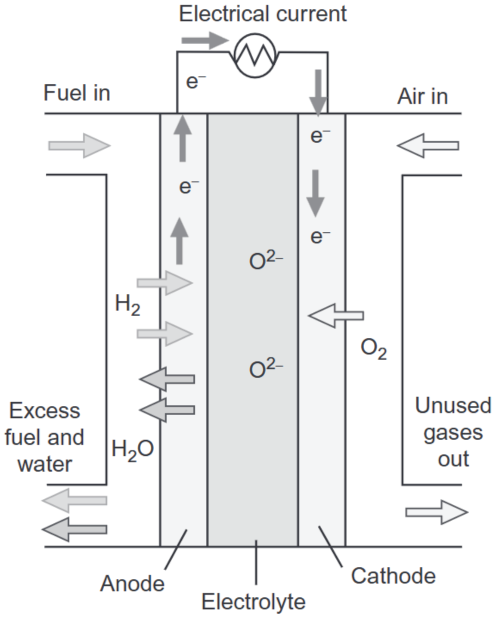

Figure 8 Schematic representation of a solid oxide fuel cell [74]

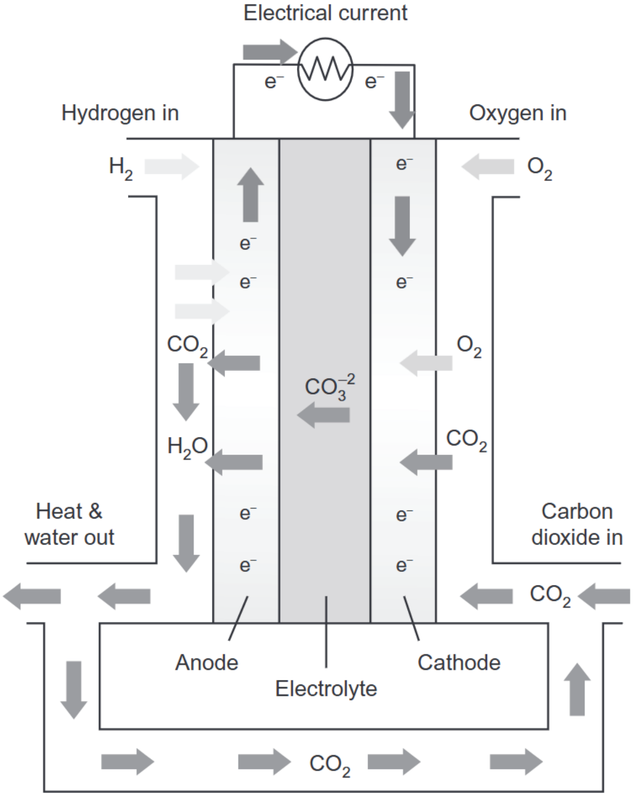

Figure 9 Schematic representation of a molten carbonate fuel cell [74]

4.1.4 Molten Carbonate Fuel Cells

Molten carbonate fuel cells (MCFC) use a molten carbonate electrolyte, typically a blend of lithium carbonate (Li_2CO_3) and potassium carbonate (K_2CO_3) which is solid at room temperature, but at operating temperatures (600-700°C) is liquid [78]. Unlike in other fuel cell technologies, in MCFCs hydrogen, oxygen and carbon dioxide are all used for the reaction as showed in Figure 9.

Hydrogen, which is supplied to the anode, reacts with the carbonate ions in the electrolyte according to:

$$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^- \qquad (7)$$

This produces water, carbon dioxide and free electrons. The electrons are transferred to the cathode via external circuit and used for generating power, water is sent to exhaust and the carbon dioxide is directly sent back to the cathode where it reacts with the oxygen to regenerate carbonate ions in the electrolyte according to:

$$O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{2-} \qquad (8)$$

The MCFCs can directly utilize hydrogen or reform hydrocarbon fuels, making them ideal for stationary power generation and cogeneration applications [79].

4.1.5 Phosphoric acid fuel cells

The Phosphoric Acid Fuel Cell (PAFC) uses phosphoric acid as its electrolyte, which is stable up to working temperatures up to 200°C. PAFCs typically operate between 150°C and 200°C and use catalysts like platinum or platinum-ruthenium alloys on porous carbon electrodes. Such higher working temperatures improve resistance to carbon monoxide poisoning and accelerate electrode reactions. Hydrogen is supplied to the anode, usually produced via reforming natural gas, and oxygen from air is supplied to the cathode, producing water and electrical power. PAFCs have moderate fuel-to-electric efficiency (36-42%) but can reach overall efficiencies up to 87% if waste heat is used for combined heat and power applications [80].

The electrolyte is pure phosphoric acid (H_3PO_4), which conducts protons (H^+) between the anode and cathode. At the anode, hydrogen molecules (H_2) are absorbed onto the electrode surface and dissociate into hydrogen atoms, Figure 10. These atoms give up electrons and pass into the electrolyte as protons:

$$2H_2 \rightarrow 4H^+ + 4e^- \qquad (9)$$

The protons migrate through the phosphoric acid electrolyte to the cathode. At the cathode, oxygen molecules (O_2) from air are absorbed and dissociate. The oxygen atoms take electrons from the external circuit and react with the protons to form water:

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \qquad (10)$$

The overall cell reaction is the combination of hydrogen and oxygen to form water:

$$2H_2 + O_2 \rightarrow 2H_2O \qquad (11)$$

4.2 Hydrogen as Fuel for Internal Combustion Engines

The development of marine hydrogen engines is gaining attention as part of efforts to reduce carbon emissions [82]. Studies suggest that addition of hydrogen to diesel fuel can improve engine performance by enabling faster and complete combustion, and reduce emissions (except for NO_x). However, literature also indicates that increasing hydrogen proportions in fuel mixtures can lead to abnormal combustion, including backfire, preignition, and knocking [109, 110]. These issues are particularly challenging in large, low-speed, high-power marine engines. Hydrogen direct injection can prevent backfire, but preignition and knocking issue risks remain due to residual hot spots and fuel mixture inconsistencies [83]. To address this, modern hydrogen engines use lean combustion and aim to improve fuel homogeneity, reducing localized high hydrogen concentrations [82].

Literature suggests that hydrogen can be used in as fuel in internal combustion engine (ICE) in two different engine groups and subdivided into additional subgroups [84]:

1) Spark ignition engine (SI),
    a) Manifold induction – Low-temperature hydrogen is injected into the manifold through a valve-controlled duct.
    b) Direct introduction – A cryogenic cylinder is used to store hydrogen. A pump circulates liquid hydrogen to a heat exchanger to vaporize it. Then, cold hydrogen is injected into the engine. By using cold hydrogen, pre-ignition is avoided and NO_x formation in the combustion process is reduced.
    c) Hydrogen addition to gasoline – A mixture of hydrogen and petrol is introduced into the combustion chamber of an internal combustion engine. Consequently, the compressed mixture is ignited by a spark.

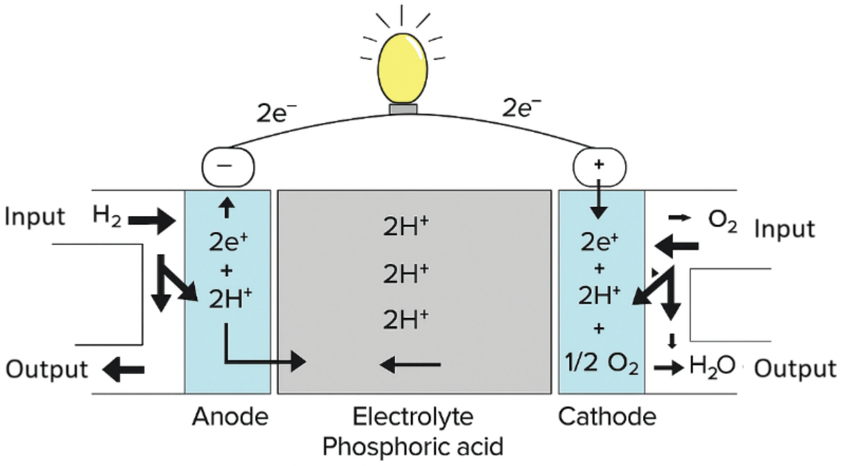

Figure 10 Schematic representation of a phosphoric acid fuel cell [81]

2) Compression ignition (CI) engine.

Spark ignition engines can be fueled with hydrogen without requiring any major modifications. Emissions of hydrocarbons and carbon monoxide are virtually negligible and the only emissions traces are produced by the evaporation and burning of the lubricating oil on engine cylinder walls.

In hydrogen-fueled compression ignition engines, the injector plays a crucial role in injecting high-pressure hydrogen into the cylinder, dictating how pressurized hydrogen enters the combustion chamber. As compression ignition engines alone cannot ignite hydrogen due to high autoignition temperature, an assistance of a spark plugs is needed. In dual-fuel engines, hydrogen serves as the primary fuel injected into the intake air, while diesel acts as the ignition source. Typically, the pilot fuel makes 10-30% of the total fuel, with hydrogen providing the majority of the energy. Analogous to spark ignition engines, nitrogen oxides (NO_x) pose a significant challenge in hydrogen-fueled dual-fuel CI engines [84].

5 Maritime hydrogen energy systems – State of the art

5.1 Fuel Cells in Maritime Sector

Fuel cells offer distinct advantages over conventional power generation methods, including greater efficiency, reduced emissions, lower noise levels, and modularity [85]. They consist of numerous individual cells arranged in stack, each containing all of the main parts as described in previous section. They can be implemented in a wide range of applications, including transportation, stationary power generation for residential, commercial, and industrial use, portable power for backup systems and electronics, and combined heat and power systems. Additionally, fuel cells can be integrated with renewable energy sources like solar and wind power to provide clean and sustainable energy solutions [86]. In this section, the latest research on fuel cells application in maritime sector is reviewed.

Van Veldhuizen et al. [77] evaluated the feasibility of using solid oxide fuel cells in cruise ship power plants. They compared different hybrid power plant configurations of systems which use marine gas oil and liquified natural gas. A component sizing model was developed in Matlab Simulink to determine the power distribution and the simulations were conducted for five-years periods to analyze systems' performances, degradation and battery requirements. The systems were compared in terms of their volume, mass, fuel consumption and emissions. The general system layout is showed in Figure 11.

Natural gas-fueled solid oxide fuel cells and internal combustion engine generator sets operating on marine gas oil or natural gas provide the electrical power. Batteries are used to balance load fluctuations. A waste heat recovery system captures excess heat from the generator sets and solid oxide fuel cells when needed,

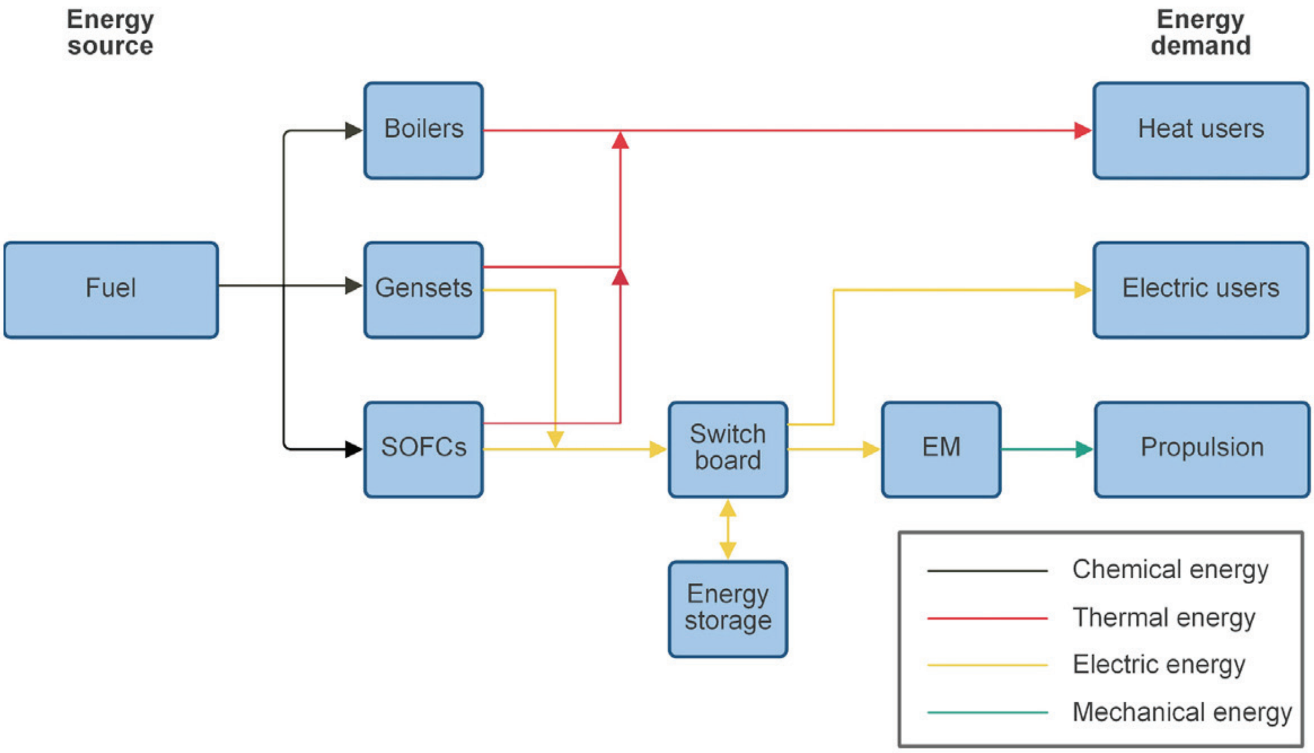

Figure 11 Solid oxide fuel cells power plant on cruise ship – a schematic representation [77]

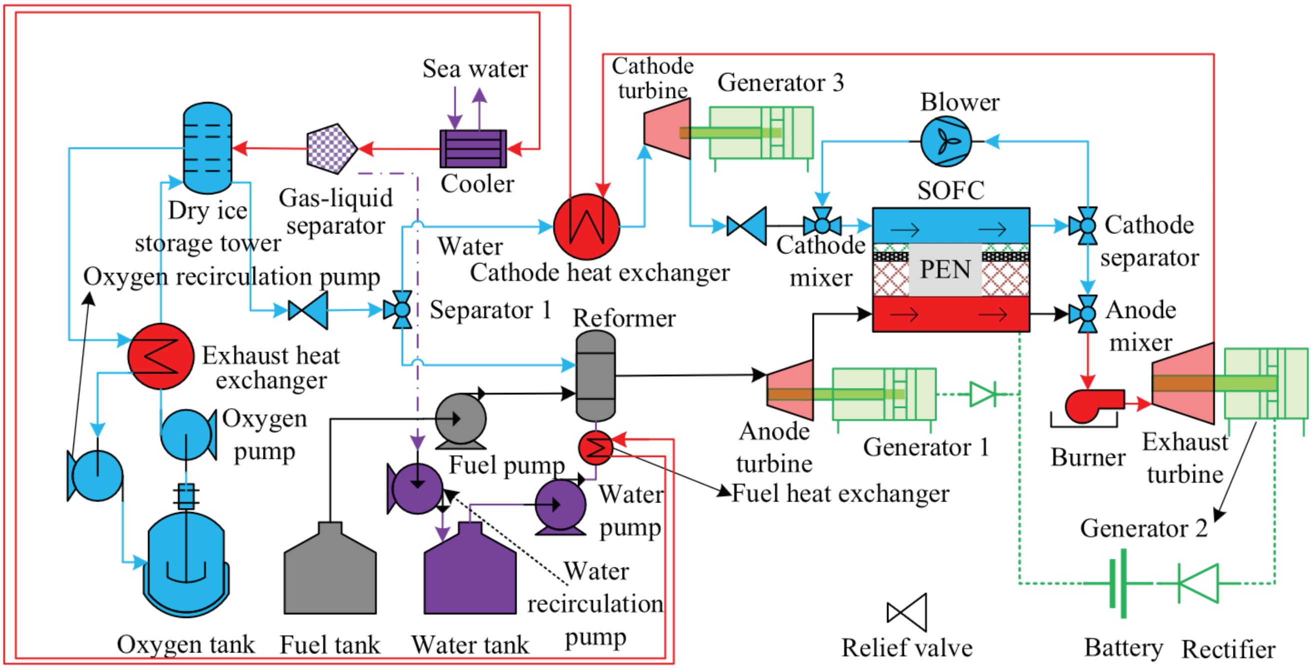

Figure 12 A scheme design of a closed solid oxide fuel cell hybrid engine for ships [75]

with boilers available for additional support. An energy management system coordinates power and heat distribution to meet demand efficiently. The authors showed that when properly sized and managed, solid oxide fuel cell systems can reduce shipping emissions by more than 30%, reaching the IMO's GHG emission reduction target for 2030.

Ji et al. [75] proposed a scheme design of a closed solid oxide fuel cell hybrid engine for ships, which is showed in Figure 12.

The system operates using liquid hydrocarbons as fuel and pure oxygen as the oxidizer, with emissions either captured or recycled, resulting in zero atmospheric discharge. It features three working fluid streams – fuel, oxygen, and exhaust; and four electricity-generating units – fuel turbine generators, oxygen turbine generators, exhaust turbine generators, and solid oxide fuel cells. The fuel stream comprises ambient temperature fuel tanks, fuel pump, reformers, turbines, water tanks, water pumps, and heat exchangers. This setup delivers hydrogen-rich gas at the required temperature and pressure to the anode side of the solid oxide fuel cells. The oxygen stream includes cryogenic oxygen tanks, pumps, heat exchangers (using both exhaust and cathode heat), turbines, blowers, and mixers. This stream supplies oxygen at controlled temperature and pressure to the cathode channels of the solid oxide fuel cells. Heat and exhaust gases from the solid oxide fuel cells are recovered through the exhaust stream, which consists of anode mixers, burners, turbines, cathode heat exchangers, coolers, gas–liquid separators, dry ice storage towers, and oxygen recirculation pumps. A portion of the cathode exhaust is recirculated via blowers to maintain the desired outlet temperature of the solid oxide fuel cells. Combusted gases expand through turbines, generating electricity via coupled generators. The turbine exhaust is initially cooled using the cathode heat exchanger, then further cooled with seawater to produce water. Carbon dioxide in the exhaust is solidified through cooling with stored oxygen and then captured. The oxygen used for cooling is re-pressurized by the recirculation pump and returned to the oxygen tank. The produced power by both the turbines and the solid oxide fuel cells is used for onboard energy needs and ship propulsion. The authors numerically analyzed the performance of the proposed system and concluded that the turbine-to- solid oxide fuel cells power ratio significantly affects system efficiency and that the optimal turbine-to- solid oxide fuel cells power ratio is 1.02–1.13. The system can achieve 67% efficiency under specified conditions, with power output adjustable from 20% to 160% of the design capacity under varying fuel flow or current density.

Di Micco et al. [87] conducted a techno-economic feasibility study on replacing an 8.3 MW diesel engine with a PEM fuel cell system on a chemical tanker ship. Storages for compressed hydrogen, liquid hydrogen and metal hydrides storage were considered. The configuration of the proposed PEM fuel cells system is showed in Figure 13.

The PEM fuel cell system generates an unregulated direct current (DC) voltage, which is then processed through a DC/DC converter and a DC/AC inverter. The resulting alternating current (AC) is distributed via an

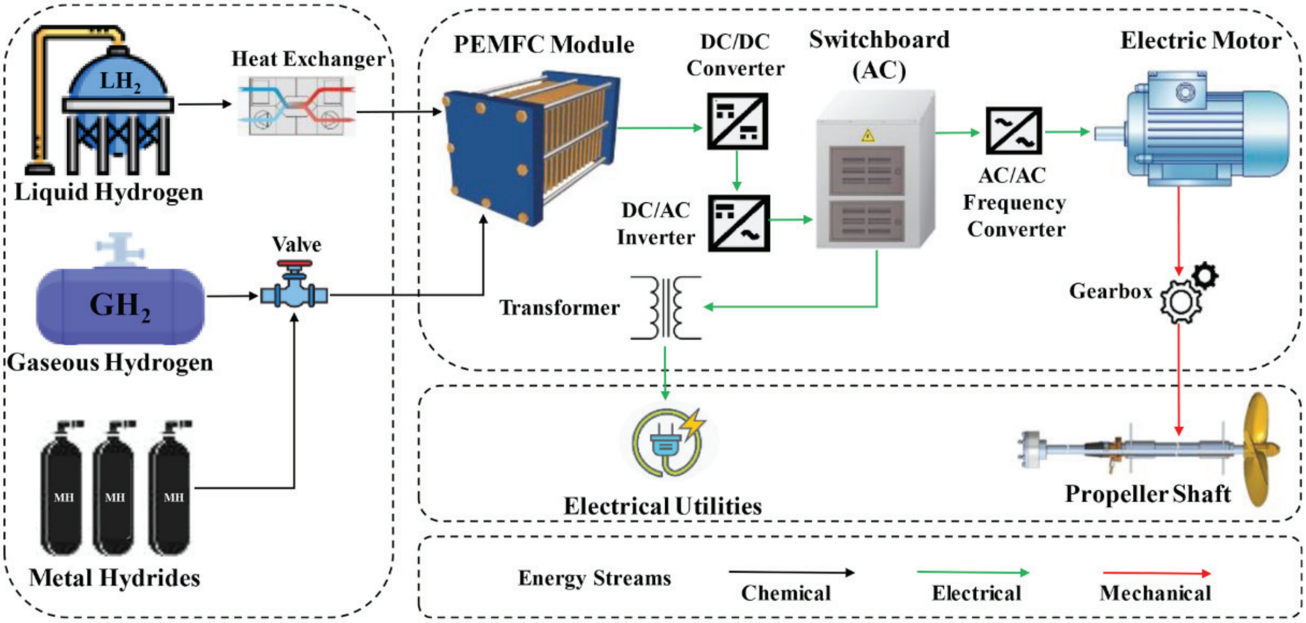

Figure 13 Proposed PEM fuel cells system for usage on tanker ships [87]

AC switchboard to power both onboard electrical systems and the electric motor. A frequency converter controls the power supplied to the electric motor, allowing for full speed range operation. The motor is linked to the propeller shaft through a gearbox.

The system was modelled in Matlab and the results showed that all analyzed systems showed significantly lower volumetric and gravimetric energy densities and therefore, additional volume and mass are required in comparison with diesel storage, the best option being the liquified hydrogen storage since it required the lowest cargo reduction of only 0.1%. When comparing only the powertrains, the fuel cell system requires 60% less volume and 56% less weight than a diesel engine. However, when storage is taken into account, the low volumetric and gravimetric densities of hydrogen result in a significantly larger required volume and greater overall weight for the fuel cell system compared to the diesel powertrain. Regarding the economic feasibility, the authors estimated that competitiveness of such systems could be viable with a hydrogen retail price of 4 $/kg, taking into account the avoided CO_2 emissions penalty cost of 112 $/tons.

Kistner et al. [76] modelled and analyzed four different battery-supported hybrid configurations of cruise ship power systems including diesel and gas combustion engines, as well as solid oxide fuel cells in order to study the economic and environmental impact of fuel cells technology in ship power systems. For a given load demand profile, the four different configurations (showed in Figure 14) were modelled with the dynamic system simulations approach and compared in terms of energy efficiency, amount of emissions and cost.

The ship capacity was 5800 persons capacity (passengers and crew). The configuration denoted with DCE-Orig. was the benchmark system that replicated the real system configuration. A total of three small and three large auxiliary engines together deliver over 59 MW of rated power. The DCE-Bat. configuration includes three large and three small diesel engines supported by a battery, creating a hybrid setup. The GCE-Bat. configuration consists of three large and three small natural gas combustion engines, also optimized for size and cost, and also with an additional battery unit. The SOFC-Bat. configuration features a variable number of solid oxide fuel cell modules, each with a natural gas reformer and a rated output of 300 kW, supported by a battery. These modules represent the target unit size envisioned for market introduction. According to the authors, the SOFC-based auxiliary power system is environmentally superior to both diesel and natural

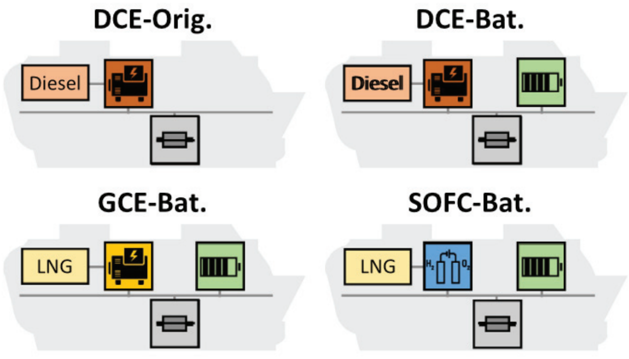

Figure 14 Different configurations of battery supported cruise ship power systems [76]

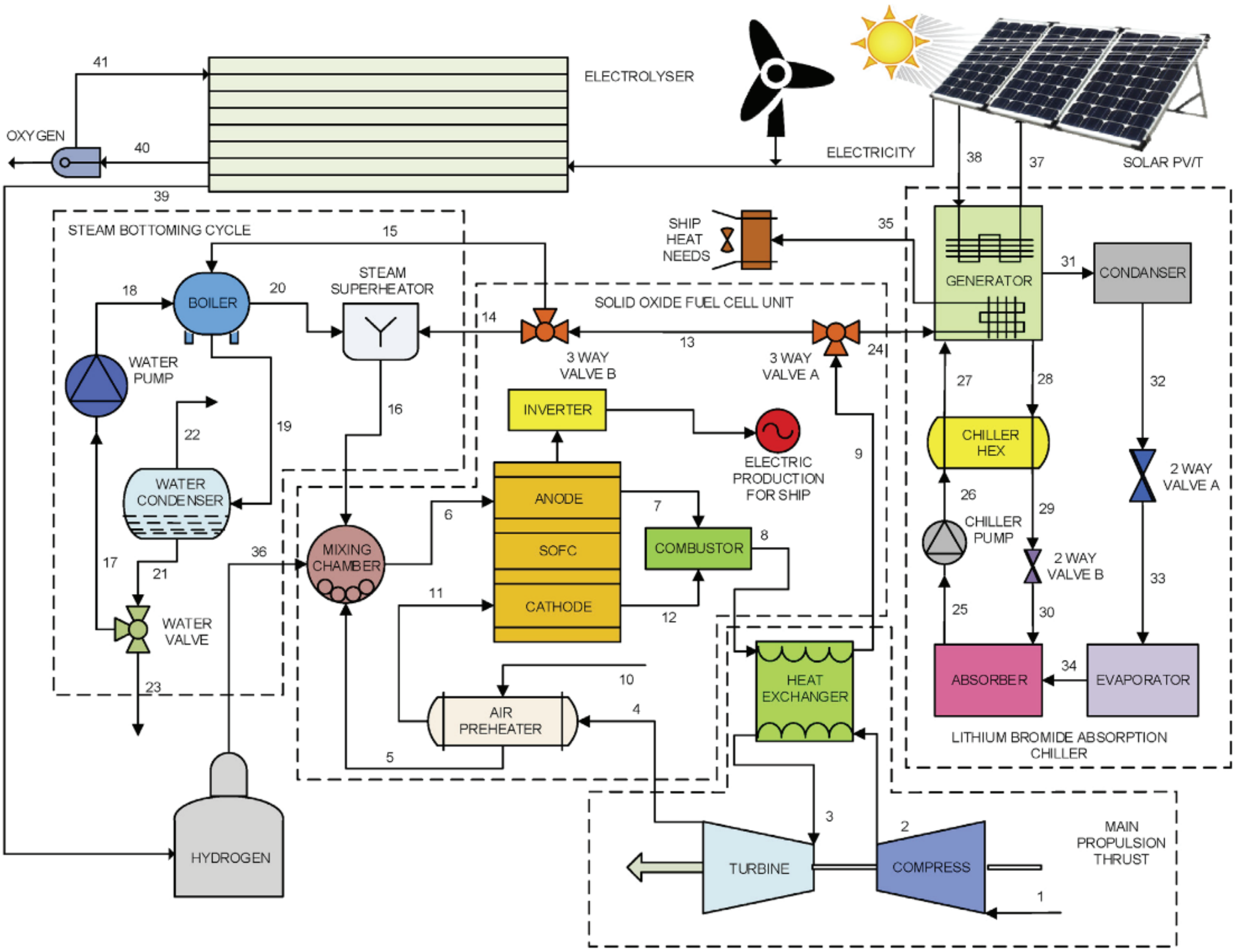

Figure 15 An integrated hydrogen fuel cell concept system for cruise ships [85]

gas engine alternatives. While gas combustion engines were identified as the most cost-effective solution in this specific case, SOFCs offer significant ecological benefits without requiring a switch to a new fuel like pre-produced h*ydrogen.*

Evrin et al. [85] conducted a thermodynamic analysis and assessment of an integrated hydrogen fuel cell concept system for ships, showed in Figure 15. The proposed system utilizes multiple renewable energy sources, including solar photo voltaic and thermal, wind turbines, and a hydrogen-fueled solid oxide fuel cell, along with a steam power plant and absorption refrigeration. It generates thrust using a 10 MW solid oxide fuel cell, 4 MW solar photo voltaic and thermal, and 6 MW wind turbines while also supplying potable water and electricity to the seacraft. A lithium bromide absorption chiller is considered for long-term food preservation, and unreacted hydrogen from the solid oxide fuel cell is used in a refrigeration cycle. Excess power is stored by producing hydrogen in a PEM electrolyzer through water electrolysis.

The authors reported that combined energy and exergy efficiency of the main propulsion, power generation from the solid oxide fuel cells, absorption chiller, and steam generators were 41.53% and 37.13%, respectively.

Ghenai et al. [88] conducted a case study on the optimal design and performance of a renewable energy system for cruise ship power in Stockholm, Sweden, aiming for proving the feasibility of a clean energy maritime transport. The system is schematically showed in Figure 16.

The authors numerically analyzed the efficiency and capacity of solar photovoltaic, PEM fuel cells, and diesel generators while assessing power output, electricity costs, and emissions. The results showed that the share of renewable energy of 13.83% was achieved, reducing the GHG and particulate emissions by 9.84% compared to conventional diesel engines. The authors emphasized that integrating solar photovoltaic and PEM fuel cells offers a cost-effective, cleaner alternative to traditional gas turbines and internal combustion engines, reducing fossil fuel dependency.

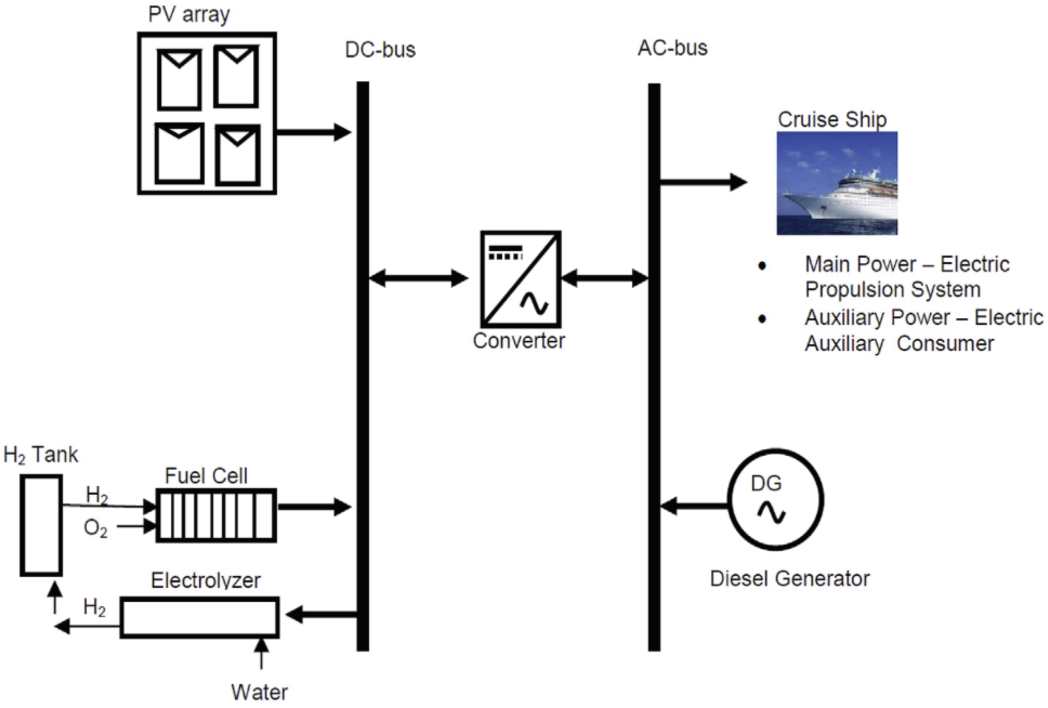

Figure 16 A renewable energy system for cruise ship [88]

Table 5 List of commercial hydrogen fuel cell powered ferries, passenger ships and support ves*sels*

Vessel	Type	Operator/ Developer	Fuel Cell System	Hydrogen Storage	Ref.
MF Hydra	Ferry	Norled	2 × 200 kW PEM fuel cells	80 m^3 liquid hydrogen tank	[89]
Sea Change	75-passenger ship	Switch Maritime	360 kW hydrogen fuel cell (Zero Emission Industries)	Not specified	[90]
ZULU 06	Inland cargo vessel	Zulu Associates	2 × 200 kW hydrogen fuel cells (Ballard)	300 kg compressed hydrogen	[91]
H2 Barge 1	Inland container barge	Not specified	3 × 275 kW PEM fuel cell units	2 × 500 kg swappable H_2 containers	[92]
H2 Barge 2	Inland container barge	Not specified	6 × 200 kW PEM fuel cell units (Ballard)	2 × 500 kg swappable H_2 containers	[92]

As the maritime industry transitions toward cleaner and more sustainable energy sources, hydrogen fuel cell technology has emerged as a promising solution for zero-emission propulsion. A number of commercial ships have already adopted this technology, particularly in regions committed to green innovation such as Northern Europe and North America. These vessels, listed below in Table 5 are mostly ferries, passenger boats, and support vessels, showcasing hydrogen's early commercial viability at small to medium scale.

5.2 Hydrogen as Fuel for Internal Combustion Engines

Although there is a strong emphasis on hydrogen fuel cells for maritime applications, research of hydrogen-powered internal combustion engines on ships can also be found in latest literature. Ventayol et al. [93] performed a comparative life cycle assessment of hydrogen internal combustion engines, hydrogen fuel cells, and diesel engines for a 400 passengers ship, originally designed to be powered by a diesel combustion engine with power 792 kW. The results indicated that both hydrogen-based propulsion systems offer significant environmental advantages over diesel engines. The authors stated that green-hydrogen-powered internal combustion engines emerge as the most suitable option from a maritime sector decarbonization point of view, followed by the fuel cells.

Hanafi et al. [94] numerically studied the impact of replacing natural gas with hydrogen in dual fuel natural gas/diesel engines with the aim to improve the combustion efficiency and reduce emissions. The results showed that replacing natural gas with hydrogen yields 2%

power increase and over 50% efficiency. Reducing diesel share to 22% at low loads significantly cuts CO_2 emission by more than 4 times, unburned methane emission by up to 33,000 times, carbon monoxide emission by up to 500 times, and formaldehyde emission by up to 2,600 times. Thermal NO_x emission remained below 0.2 g/kWh, meeting EURO VI standards. Despite safety concerns, unburned hydrogen emissions are minimal, at less than 0.3% of the fuel entering the engine.

Serrano et al. [95] conducted experimental research with the goal to find the optimal combination of injection parameters and hydrogen energy share for maximizing the efficiency while keeping the NO_x emissions in restrained levels. The measurements were performed on a turbocharged 4-cylinder marine compression-ignition engine with double pilot fuel injection which operated in electricity generator mode on-board, under diesel-hydrogen dual fuel. The authors stated that the engine efficiency can be improved from 38.6% when only diesel fuel is used to 40.1% when small quantity (2-3%) of hydrogen is added the fuel.

Oktar et al. [96] examined the potential of retrofitting conventional internal combustion engines to operate on hydrogen fuel. The authors emphasized a critical challenge: engine power output and the amount of NO_x emissions are closely interconnected in a way that when hydrogen engines operate at high power levels, the amount of NO_x emissions increases significantly, while ultra-lean conditions reduce the emissions but lead to lower power output. This trade-off ultimately limits the large-scale application of hydrogen-fueled engines, particularly in sectors demanding both high efficiency and strict emission compliance. Addressing this issue requires further optimization of engine operation and the implementation of advanced exhaust gas after-treatment systems.

Piano et al. [97] conducted an experimental analysis to evaluate the effects of key engine calibration parameters on the performance and emissions of a 6-cylinder, 12.9-liter heavy duty engine, retrofitted to utilize direct injected hydrogen spark ignition instead of natural gas. The research focused on the influence of air-fuel equiva-

Table 6 Various concepts of hydrogen engine technologies for usage in maritime industry currently in development or testing phase

Company	Technology type	Key features	Hydrogen usage capability	Current status	Ref.
MAN ES	Dual-fuel	Allow fuels with up to 25% H_2 with full power on liquid fuel	Dual-fuel: up to 25% H_2	Commercially available	[99]
MAN ES	Compression ignition	50-bore MAN B&W two-stroke engine tested up to 100% load with 95% GHG reduction	100% H_2	Under development and in testing phase	[99]
MAN Truck and Bus	Dual-fuel for Workboats	2× V12 diesel engines (MAN D2862 LE448), 749 kW each Equipped with selective catalytic reduction exhaust gas aftertreatment system	Dual-fuel with H_2 injection	Serial operation started May 2022	[100]
Rolls Royce (MTU)	Hydrogen ICE (MTU Series 4000)	Successfully tested 12-cylinder engine on 100% H_2 in 2023 – Current gensets: up to 25% gas blending	100% H_2 or up to 25% gas blending in operation	MTU Series 500/4000 gas engines available with blending capability	[101]
Wärtsilä & WEC Energy	Hydrogen-blended ICE	Wärtsilä 50SG engine tested with 25% H_2 blend 95% engine load achieved, with efficiency gains	25% H_2 blending	Tested in 2022 at A.J. Mihm plant, Michigan	[102]
Cummins	Hydrogen ICE	In 2021 medium-duty H_2 engine achieved 1098 Nm & 290 hp In 2022 a 15-liter hydrogen engine unveiled at ACT Expo	100% H_2 targeted	Technology tested and showcased; commercial models in development	[103]
Caterpillar	Generator Sets	– Operates on natural gas with up to 25% H_2 – G3516 demonstrator capable of 100% H_2 – Power range: 600 kW–2.5 MW	Up to 25% H_2 (blended); G3516: 100% H_2	100% H_2 genset offered since 2022	[130, 131]
CMB.TECH	Dual-fuel H_2ICE System	– Injects H_2 into air inlet; displaces traditional fuel – CO_2 reduction proportional to H_2 input – Retrofits existing engine systems	Dual-fuel with variable H_2 injection	Technology designed for flexibility and compatibility with existing diesel engines	[104]

lence ratio, spark advance, and injection timing on combustion characteristics and emissions formation. The authors indicated that retarding injection timing can improve engine efficiency by approximately 1.5%, but at high air-fuel ratios (around 2.9), it can lead to a more inhomogeneous mixture, increasing combustion variability and NO_x emissions. Additionally, combustion timing adjustments show that lean mixtures are particularly sensitive to combustion retard, with peak efficiency achieved at air-fuel ratio of 2.9 under advanced timing conditions.

Shahid et al. [98] conducted an experimental and numerical study to explore the potential benefits of utilizing waste heat of a hydrogen-enriched internal combustion engine for hydrogen production and to enhance the overall efficiency of hydrogen-enriched compressed natural gas engines. The authors used ASPEN Plus software to model the system. Experimental analysis was conducted under specific conditions, including a hydrogen ratio of 20%, exhaust gas recirculation ratio of 20%, engine load of 75%, and speed of 1200 rpm, to evaluate the potential of waste heat recovery. The main findings indicated that the engine's exhaust temperature reached a maximum of 701 °C, with an available exhaust heat of 134 kW. Increasing the reformer temperature from 700 °C to 1000 °C led to a 23.31% rise in hydrogen production, which reached 5.62 kg/h with a steam temperature of 600 °C. Under these optimized conditions, the engine efficiency was recorded at 36.44%, while the overall system efficiency improved significantly to 62.23% after hydrogen production. The authors emphasized the potential of integrating waste heat recovery with hydrogen production to enhance engine performance and sustainability.

Some various concepts of hydrogen engines technologies for usage in maritime industry that are in different development and testing phases are systematically reviewed in Table 6.

6 Discussion

The reviewed literature emphasizes significant safety challenges for hydrogen storage and usage in maritime transport sector, primarily due to hydrogen's high flammability, leakage risks, and sensitivity to marine environmental conditions such as corrosion, vibration, and collision damage. Design choices for storage play a critical role: while open-deck storage lowers the likelihood of hydrogen accumulation and fire hazards, it exposes systems to harsh external forces and may negatively affect vessel stability, whereas under-deck storage increases the risk of combustible cloud formation. Additionally, existing LNG and CNG standards provide only a partial foundation, as hydrogen's unique properties such as material embrittlement, small molecular size, and low ignition energy require tailored approaches. Computational tools like CFD simulations have also proven valuable in assessing dispersion scenarios, underscoring the need for their use in informing safety guidelines and regulatory development.

Despite these insights, several research gaps remain evident. Much of the current understanding is based on simulations rather than empirical, real-world testing of hydrogen storage and bunkering in marine environments. Hydrogen-specific design standards are yet to be determined, since relying on modified LNG or CNG rules does not adequately account for hydrogen's unique behavior. Long-term studies of environmental effects such as salt exposure, thermal cycling, and vibrations on hydrogen systems are limited, and scalable solutions for bunkering large vessels remain underexplored, as most demonstrations focus on smaller ferries or regional shipping. Moreover, strategies for emergency response to hydrogen leaks, fires, or explosions in port and shipboard contexts are not yet sufficiently developed, leaving significant knowledge gaps in operational safety preparedness.

Logistical obstacles further complicate the adoption of hydrogen in maritime applications since ports generally lack the necessary infrastructure, including bunkering facilities, pipelines, and safety zones, to integrate hydrogen effectively. Liquefied hydrogen also presents additional operational complications related to boil-off management and energy-intensive cryogenic storage. Finally, the scalability of current hydrogen refueling systems is limited, with existing projects remaining at pilot scale and not yet sufficient to support the global shipping sector.

7 Conclusion

Hydrogen is gaining prominence as a crucial component in the shift toward a low-carbon energy future, because of its adaptability, high energy density, and potential for emission-free utilization. Various production methods offer different benefits and trade-offs. Steam methane reforming remains the most cost-effective and widely used method, but it generates significant CO_2 emissions unless combined with carbon capture, utilization, and storage. Electrolysis is a clean and scalable alternative, especially when powered by renewable sources, yet it remains costly and electricity-intensive. Biomass gasification, when paired with carbon capture, utilization, and storage, can be nearly carbon-neutral, although efficiency losses and inconsistent feedstock quality present challenges. Photoelectrochemical water splitting offers a promising future route, though it is currently in the early stages with low conversion efficiency. Nuclear-based hydrogen production enables continuous, large-scale output but is limited by high costs and safety concerns.

In terms of hydrogen color classification, grey hydrogen is the most affordable but also the most environmentally damaging. Blue hydrogen reduces emissions via carbon capture, utilization, and storage but still relies on fossil fuels. Green hydrogen, produced using renewable energy, is the cleanest and most sustainable option, though it remains economically prohibitive. However, as technology matures and renewable energy costs fall, green hydrogen is expected to become a leading clean energy source.

Hydrogen storage technologies are essential for enabling its widespread adoption across industries. Compressed hydrogen storage, particularly through pressure vessels, is commonly used and reliable, though heavy and limited in volumetric efficiency. Liquid hydrogen storage, while technically demanding due to insulation and boil-off issues, is crucial for long-distance transport and large-scale applications. Solid-state storages using metal hydrides and hybrid materials like metal organic frameworks hold promise, but current materials do not yet meet required performance standards for commercial use, especially in light-duty vehicles. Ongoing research into materials with higher gravimetric density and improved kinetics is essential to advance these solutions.

Hydrogen's diverse applications ranging from fuel cells for transportation and portable power, to industrial heating, electricity generation, and long-term energy storage, demonstrate its broad potential. Fuel cell technology, particularly polymer electrolyte membrane and solid oxide fuel cells, is advancing rapidly and offers clean, efficient, and adaptable energy solutions. As these systems become more cost-competitive, their adoption is expected to grow across multiple sectors.

Despite challenges related to cost, infrastructure, and energy efficiency, hydrogen stands as a promising alternative fuel of future clean energy systems. Continued investment in production technologies, innovative storage solutions, and supportive policy frameworks will be key to unlocking hydrogen's full potential and integrating it into a resilient, sustainable global energy landscape.

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