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Fueling the future: A comprehensive review of hydrogen energy systems and their challenges

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HIGHLIGHTS

- Critical review of hydrogen for global energy needs and climate change is presented.
- Potential applications and characteristics of hydrogen energy are scrutinized.
- New technology and regulations are critical to developing hydrogen energy systems.
- Acceptance and increased use of hydrogen energy are driven by increased awareness.
- Future studies on hydrogen should include sustainability, safety, and feasibility.

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ABSTRACT

This comprehensive study assesses the current state of the hydrogen energy system and investigates its potential to transform the global energy landscape while addressing important concerns about climate change. While hydrogen energy has numerous advantages, including sustainability and cleanliness, it faces substantial challenges in the areas of storage, manufacturing, distribution, infrastructure, safety, and cost. Scholars, lawmakers, business leaders, and the general public must all work together to address these complex issues. The research emphasizes the significance of breakthrough technology and astute government policies for the successful development and widespread deployment of hydrogen energy systems. It highlights that this revolutionary effort cannot be performed in solitude. Public education and enhanced awareness appear to be significant factors in promoting greater acceptance and use of hydrogen energy. Furthermore, the study identifies critical future research objectives. It underlines the importance of enhancing the efficiency, sustainability, safety, and economic feasibility of hydrogen energy systems. The development of new storage systems, superior infrastructure designs, and seamless integration technologies is vital to achieving the full potential of hydrogen energy. Finally, the research presented here gives a critical assessment of the hydrogen energy situation and outlines a roadmap toward a more sustainable and resilient future. The review's conclusions are significant for policymakers, academics, and stakeholders because they provide

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critical insights into the opportunities and problems associated with realizing the full potential of hydrogen energy.

1. Introduction

For decades, fossil fuels have been the world's principal source of energy, enabling economic progress, industrialization, and technical innovation [1,2]. Unfortunately, the usage of fossil fuels has enormous environmental consequences that endanger our world [3,4]. The production of greenhouse gases such as carbon dioxide during the extraction, transportation, and burning of fossil fuels is a fundamental environmental issue [5–7]. These gases cause global warming, which can lead to climate change with serious environmental, societal, and economic repercussions [8–10]. Moreover, the exploitation of fossil fuels may degrade the environment and disrupt ecosystems via pollution, deforestation, and habitat degradation [11,12]. Transportation of fossil fuels, like oil, also entails spill and accident hazards, which may have serious consequences for the environment and human health [13,14]. Additionally, fossil fuel supply networks are vulnerable to geopolitical and economic instability, which can result in supply interruptions and price volatility [15]. This insecurity can exacerbate political tensions and conflicts, worsening environmental and socioeconomic dangers [16].

The Sustainable Development Goals (SDGs) and hydrogen are intended to promote the development of clean and sustainable energy systems. Hydrogen, as an energy carrier, has the potential to significantly contribute to the achievement of the SDGs [17]. Hydrogen is critical in accelerating the transition to clean, renewable energy sources, serving as a long-term substitute for fossil fuels [18,19]. Renewable hydrogen can be used to generate electricity, transportation, and heat, expanding access to affordable and clean energy [20]. By providing a clean, sustainable, and diverse energy source, hydrogen can assist address such environmental and supply chain challenges [21–23]. Hydrogen may be created from a number of renewable sources, namely sun, wind, and biomass, all of which produce no greenhouse emissions [24,25]. Moreover, hydrogen may be utilized in fuel cells to create power while emitting no hazardous pollutants [26–28]. Hydrogen is especially appealing in the transportation sector, as it could be utilized in fuel cell vehicles to create zero-emission propulsion [29,30]. Hydrogen fuel cell cars have the potential to drastically cut greenhouse gas emissions from the transportation sector, which accounts for a sizable portion of world emissions [31]. Concerning supply chain difficulties, hydrogen may be generated and stored locally, minimizing reliance on imports and supply chain hazards [32,33]. Additionally, hydrogen may be delivered using existing infrastructure such as pipelines, tankers, and vehicles, decreasing the need for new infrastructure and the dangers associated with transportation [34,35].

With rising interest in hydrogen energy systems, a thorough examination of the current technologies, applications, trends, and challenges associated with hydrogen energy systems is required. A critical review article can provide a comprehensive summary of current advances in hydrogen energy systems while also assisting in the selection of the most promising technologies and applications. A study of this nature can also highlight the major constraints and limitations of current hydrogen technologies, as well as provide insight into research areas that require more attention. As a result, the goal of this work is to provide a comprehensive and critical examination of hydrogen energy systems. This study will cover the most recent advances in hydrogen generation, storage, and transportation, in addition to the diverse applications of hydrogen in various industries. It will also examine the main constraints and limits of present hydrogen technologies, such as cost, safety, and infrastructure needs, as well as the research areas that need to be prioritized to overcome these obstacles.

Based on the review's overall goal, a comprehensive search of several academic databases would be performed to identify relevant articles, research papers, and published information in respectable journals and conferences. The search phrases would be tailored to cover every facet of the topic, including hydrogen technology, implementations, trends, and problems. Then, to select the most relevant and high-quality sources, a screening process would be carried out. The inclusion criteria would be based on the relevance, dependability, and validity of the literature. The selected literature would then be critically analyzed, with the findings synthesized to provide a thorough overview of the field's current state. The evaluation will be organized to address many elements of hydrogen-based energy systems, such as technical development, applications in diverse industries, market trends, policy and regulatory frameworks, and hurdles to broad hydrogen energy adoption. A qualitative synthesis of the examined literature would be used, with an emphasis on detecting patterns, trends, and developing concerns. The critical assessment would also include an examination of the results' implications for future research and policy development. Overall, the study would give a thorough examination of hydrogen energy systems, including insights into the current status of the field and future research and development prospects.

2. Hydrogen production technologies

2.1. *Steam methane reforming*

Steam methane reforming (SMR) is a method of producing hydrogen from methane and other hydrogen-containing chemicals, which is the principal component of natural gas [36,37]. SMR involves the reaction of methane with steam in the availability of a catalyst to generate hydrogen gas, carbon

monoxide, and carbon dioxide [38,39]. A water-gas shift reaction is then used to remove the carbon monoxide as well as dioxide. SMR is the most widely used technique to generate hydrogen, accounting for roughly 95% of global production [40,41]. This is because natural gas, which serves as the process's feedstock, is widely available and inexpensive. Furthermore, SMR is highly efficient and produces high-purity hydrogen. SMR comes in numerous flavors, including autothermal reforming (ATR) and partial oxidation (POX), both of which employ natural gas as a feedstock [42,43]. POX utilizes the direct burning of natural gas to create hydrogen and carbon monoxide, whereas ATR combines SMR with a partial oxidation process. SMR, on the other hand, has certain environmental problems because it emits greenhouse gases like carbon dioxide [44]. SMR's carbon impact is being reduced by incorporating carbon capture and storage (CCS) technology or using renewable energy sources to power the process [41,45]. A typical flow chart for SMR is depicted in Fig. 1.

Because of the growing demand for clean and sustainable energy sources, the potential application of hydrogen production technologies, which include steam methane reforming, looks promising. As the world continues to move away from petroleum and coal and more towards renewable energy sources, hydrogen is establishing itself as a key player in the clean energy landscape [46]. The use of renewable energy sources such as wind and solar power to power the production process is one possible future direction for hydrogen production [47,48]. This approach, dubbed “green hydrogen,” has the potential to significantly reduce the carbon footprint of hydrogen production and transform it into a more environmentally friendly and sustainable energy source. The use of hydrogen in fuel cells for transportation and other uses is another interesting area of research [49,50]. Fuel cell cars have the potential to transform the transportation sector since they emit no greenhouse gases and have comparable range and performance to regular petrol vehicles. Moreover, research is being conducted to enhance the efficiency and lower the cost of hydrogen-generating technologies such as SMR. This might make hydrogen production more competitive with old fossil fuels, hastening the transition to a hydrogen-based economy [51,52].

2.2. *Electrolysis*

Hydrogen is an adaptable and clean energy carrier that may be produced through a variety of methods, including electrolysis [53]. The process of splitting water into hydrogen and oxygen using electricity is known as electrolysis [51]. Alkaline, polymer electrolyte membrane (PEM), and solid oxide electrolysis cells are examples of electrolysis technologies (SOECs) [54,55]. Alkaline electrolysis is the oldest and most widely used electrolysis technology for producing hydrogen. It operates independently at high temperatures and pressures and has low efficiency, but it is well-known and has a long operating life [56]. PEM electrolysis, on the other hand, is more efficient and operates at lower temperatures and pressures than alkaline electrolysis [57]. It is ideal for small-scale applications and may be combined with renewable energy sources like solar and wind power [58,59]. SOECs are a newer high-temperature technology that can be utilized for both hydrogen generation and fuel cell applications. They provide great efficiency and flexibility in terms of energy input, but they are still in the early phases of development and are not yet economically feasible. Overall, electrolysis is a promising hydrogen manufacturing process, especially when driven by renewable energy sources [60]. However, the cost and efficiency of electrolysis equipment remain key hurdles that must be overcome before hydrogen can be widely used as a sustainable energy carrier [61–63]. A typical flow chart for hydrogen production through electrolysis is depicted in Fig. 2.

Electrolysis-based hydrogen production is a promising technology that has the potential to play a critical role in the transition to a low-carbon economy [64]. However, several obstacles must be overcome before this technology can be widely adopted. Electrolysis's high energy requirements are a significant challenge, as significant amounts of electricity are required to produce hydrogen [65]. Furthermore, the cost of producing hydrogen via electrolysis remains high when

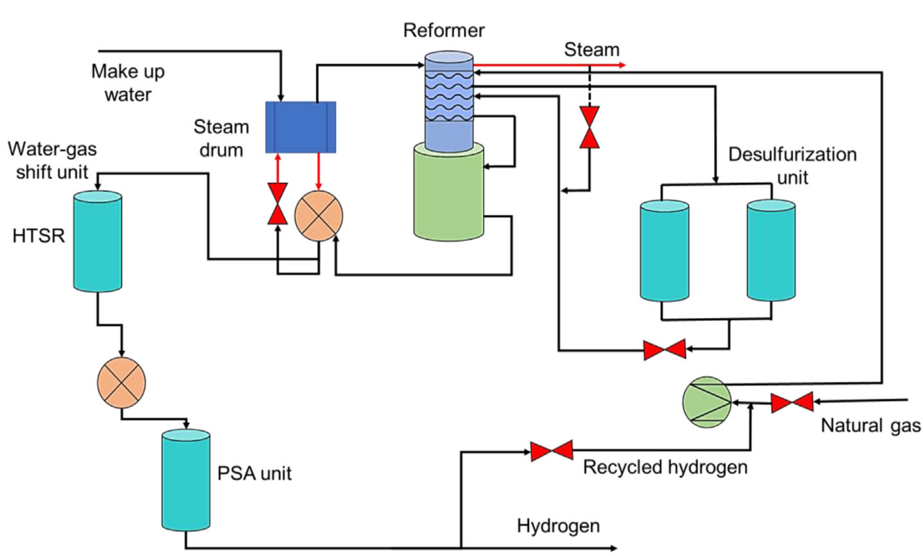

Fig. 1 – Hydrogen production via steam reforming of methane [38].

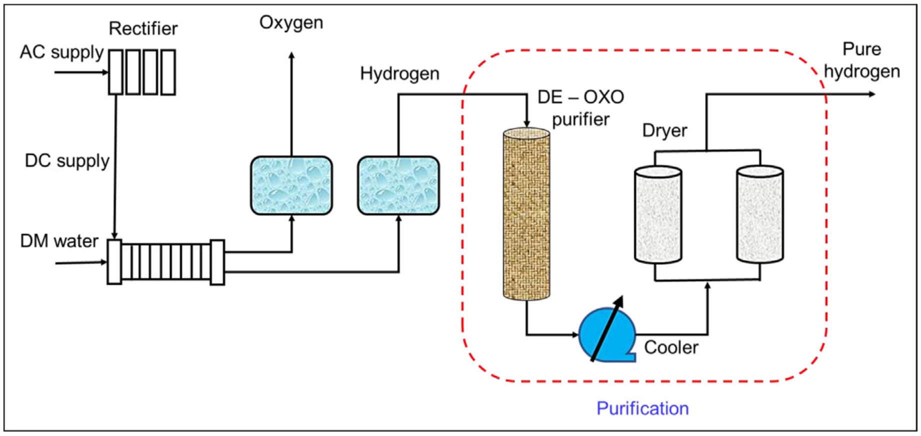

Fig. 2 – A typical flow chart for hydrogen production through electrolysis.

compared to other methods of producing hydrogen [66,67]. Technical issues concerning the efficiency and sturdiness of electrolysis systems must also be addressed [68]. Despite these obstacles, there is a significant prospect for the future of electrolysis-based hydrogen production [69]. Researchers are working to improve electrolysis system efficiency, and the incorporation of renewable energy sources may offer an environmentally friendly and carbon-neutral source of electricity for electrolysis [70]. The widespread use of hydrogen as a fuel source could be enabled by large-scale production and the development of efficient hydrogen storage and distribution systems [71–73]. Overall, while challenges remain, it is expected that ongoing research and development will overcome these obstacles and enable broad acceptance of hydrogen as a clean energy source.

2.3. *Thermochemical processes*

Heat is used to drive a series of chemical reactions that eventually produce hydrogen in thermochemical processes [74–76]. There are several types of thermochemical processes, but the sulfur-iodine (SI) cycle is the most promising for large-scale hydrogen production. The SI cycle consists of three major steps. Heat is used to decompose sulfuric acid (H_2SO_4) into sulfur dioxide (SO_2), oxygen (O_2), and water (H_2O) in the first step [77,78]. This is a highly endothermic reaction that requires a temperature of around 850 °C. In the second step, the SO_2 produced in the first step is oxidized by oxygen in the presence of a catalyst to form sulfur trioxide (SO_3). This reaction produces a lot of heat, which can be used to power the first step [79,80].

The SO_3 is then reacted with water to form sulfuric acid, which can then be recycled back to the first step. This reaction generates heat, which can be used to power the next step. The SI cycle results in the decomposition of water into hydrogen and oxygen [81,82]. The first step produces hydrogen by reacting water with SO_2, while the second step produces oxygen by oxidizing SO_2 to SO_3. In comparison to other thermochemical processes, the SI cycle has several advantages. It has a theoretical maximum efficiency of around 50% and can use a variety of heat sources, including nuclear, solar, and fossil fuels. Researchers are working to improve electrolysis system efficiency, and the incorporation of renewable energy sources may offer an environmentally friendly and carbon-neutral source of electricity for electrolysis. The widespread use of hydrogen as a fuel source could be enabled by large-scale production and the progression of efficient hydrogen storage and distribution systems. Overall, while challenges remain, it is expected that ongoing research and development will overcome these obstacles and enable broad acceptance of hydrogen as a clean energy source [78,83].

Furthermore, the SI cycle emits no greenhouse gases or other harmful emissions. However, the SI cycle presents a number of challenges that must be addressed. It necessitates highly corrosive materials and processes, and the development of materials capable of withstanding the harsh conditions of the SI cycle remains a challenge. Furthermore, the SI cycle requires a substantial amount of electricity, and the pricing of hydrogen produced through this process is presently greater than that of hydrogen produced through other methods. The SI cycle, in particular, has the potential to become a key technology for large-scale hydrogen production. While there are still challenges with this technology, ongoing research, and development are expected to overcome these obstacles and enable the widespread adoption of thermochemical processes for hydrogen production [79,84,85]. A typical SI cycle is depicted in Fig. 3.

The production of hydrogen via thermochemical processes presents a number of challenges and future opportunities [87,88]. The high energy requirements of this method are one of its main drawbacks [89]. The production of hydrogen via thermochemical processes necessitates high temperatures and energy inputs, so it may be costly when compared to other methods [90]. Corrosion and material compatibility are also issues that arise when using thermochemical processes to produce hydrogen [82]. The high temperatures and corrosiveness of some of the chemicals employed in these processes can cause corrosion and material compatibility problems, reducing equipment lifespan and increasing maintenance costs. Furthermore, thermochemical processes

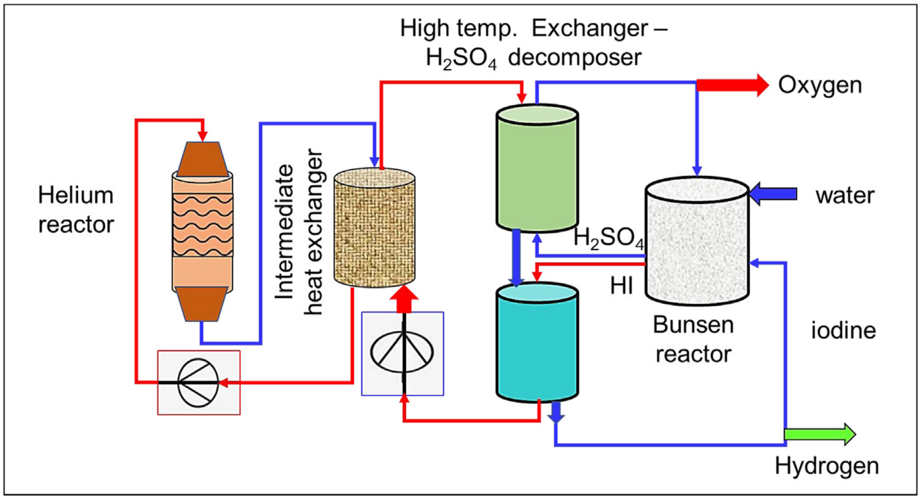

Fig. 3 – SI cycle flow chart for hydrogen production [86].

are complex and necessitate precise control of various parameters in order to maximize hydrogen yield [91]. Any variability or errors in the process can result in lower yields or lower hydrogen quality. Despite these challenges, the future potential of thermochemical hydrogen production is promising. One of the primary goals of R&D in this area is to improve efficiency by optimising the process and reducing energy demands. To reduce greenhouse gas emissions and reliance on fossil fuels, thermochemical processes can also be energised by renewable energy sources such as solar or wind power [92,93]. Furthermore, thermochemical processes can be combined with carbon capture and storage technologies to acquire and store the carbon dioxide generated in the process, assisting in the reduction of greenhouse gas emissions and mitigating climate change.

Ultimately, thermochemical processes can be upscaled to an industrial scale to meet the increasing demand for hydrogen as a transportation and energy storage fuel. However, this will necessitate significant investment in R&D as well as the establishment of large-scale manufacturing plants.

2.4. *Biological processes*

Biological hydrogen generation is a promising approach for producing sustainable and renewable hydrogen. It is an alternative to standard hydrogen production technologies like steam methane reforming as well as coal gasification, which are connected with greenhouse gas emissions [94]. Following are a few of the biological processes, as shown in Fig. 4, being employed for hydrogen production.

Dark fermentation is the fermentation of organic substrates by anaerobic bacteria in a dark environment [95]. Bacteria degrade organic substrates like glucose to create hydrogen gas, carbon dioxide, as well as other by-products [96]. Clostridium species and Enterobacter aerogenes are two bacteria that are widely employed in this technique [97,98].

Photo fermentation is a process that uses photosynthetic microbes to generate hydrogen gas in the presence of light [99]. Light energy is used by bacteria to convert organic substrates like acetate into hydrogen gas, carbon dioxide, and other by-products. Rhodobacter sphaeroides and Rhodopseudomonas palustris are two commonly used bacteria in this process [97,98,100].

Cultivation of algae: This process involves growing algae, which are photosynthetic microorganisms [101]. Photobiological water splitting is a process by which algae produce hydrogen gas. Light energy is used in this process to split water into hydrogen and oxygen. Chlamydomonas reinhardtii and Scenedesmus obliquus are two common algae used in this process [102,103].

Microbial electrolysis cell: This process uses microbial fuel cells to generate hydrogen gas. Anode-respiring bacteria are used in the process to break down organic matter and release

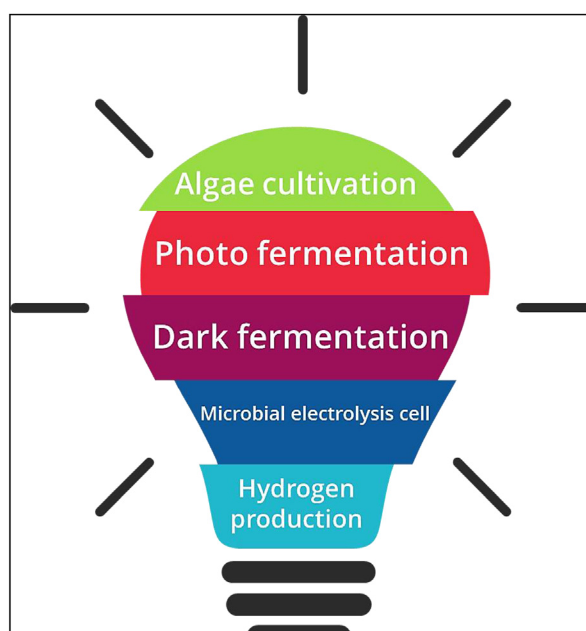

Fig. 4 – Hydrogen production through biological means.

electrons [104]. The electrons are transferred to the anode, which causes an electrical current to flow. After that, the electrical current is used to split water into hydrogen and oxygen [32,105].

Finally, biological hydrogen production processes provide sustainable and renewable energy solutions. Different microorganisms are used in the processes to convert organic substrates or water into hydrogen gas. These processes, however, are still in the research and development stage, and further improvements are required before they can be economically viable for large-scale hydrogen production. While biological techniques for hydrogen production show enormous promise, some various problems and limits must be solved before they can be put into practise. The following are some of the obstacles and limitations of biological hydrogen production.

Low hydrogen yield: Biological processes often produce less hydrogen than conventional processes. This means that more feedstock is needed to create the same amount of hydrogen [106].

Poor conversion efficiency: Biological processes often have a lower conversion efficiency than conventional processes. This means that a large amount of the feedstock is transformed into by-products like carbon dioxide and methane [107].

Contamination: Unwanted bacteria can contaminate biological processes, affecting the hydrogen production process [106,108].

High capital and operating costs: Biological hydrogen production currently has higher capital and operating costs than conventional processes.

Scale-up: Moving biological hydrogen production from the laboratory to the industrial scale is difficult and expensive [109,110].

Despite these obstacles, there are several opportunities and prospects for biological hydrogen production in the future, as depicted in Fig. 5. Some examples are shown in Refs. [111–113].

From Fig. 5, it can be seen that biological hydrogen production is a more sustainable and renewable alternative to traditional hydrogen production methods. For waste-to-energy, biological hydrogen production can use waste materials as feedstock, such as agricultural waste and wastewater. In the case of carbon-neutral; because the carbon dioxide produced can be captured and stored, biological hydrogen production can be carbon-neutral or even carbon-negative. For integration with other processes, to produce multiple products and reduce costs, biological hydrogen production can be integrated with other processes such as biorefineries and wastewater treatment. Relating to technological advancements: Technological advancements such as genetic engineering and synthetic biology are expected to improve the efficiency and yield of biological hydrogen production. To summarize, while biological hydrogen production has a number of challenges and limitations, it also provides significant opportunities and prospects for sustainable and renewable hydrogen production.

3. Photobiological processes

Photobiological techniques include the employment of microorganisms to transform solar energy into useable forms of energy such as hydrogen gas. Hydrogen synthesis via photobiological processes employs photosynthetic microorganisms such as cyanobacteria, green algae, and purple bacteria [114]. The following stages are involved in the photobiological hydrogen generation process [114–116].

Cultivation of photosynthetic microorganisms: Photosynthetic microorganisms are grown under regulated circumstances such as temperature, light intensity, and nutrition availability. Cultivation is often carried out in photobioreactors or open ponds.

Growth and biomass accumulation: Microorganisms need sunshine and nutrients to develop and accumulate biomass. The bacteria create oxygen as a byproduct of photosynthesis during this process.

Initiation of hydrogen production: Anaerobic conditions are used to promote hydrogen synthesis in microorganisms. This is accomplished by either cutting off the oxygen supply to the bacteria or purging the system with an inert gas such as nitrogen.

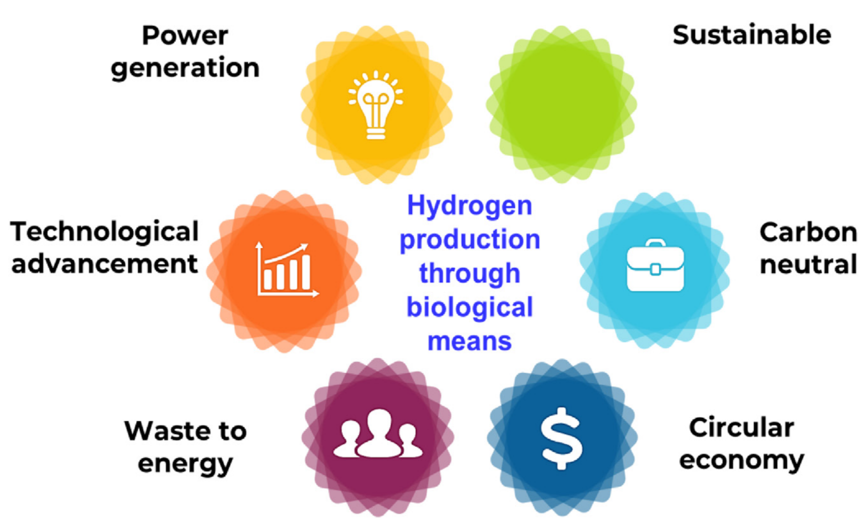

Fig. 5 – Prospects of hydrogen production through biological means.

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Production of hydrogen: Under anaerobic circumstances, bacteria convert from producing oxygen to producing hydrogen gas, a process known as photosynthetic hydrogen production. The hydrogen gas is then collected and cleaned before being used.

There are various advantages to producing hydrogen using photobiological processes. To begin with, the procedure is ecologically beneficial because it does not entail the use of fossil fuels. Second, the technique makes use of solar energy, which is plentiful and renewable. Finally, the technique uses wastewater or other waste streams as a source of nutrients, lowering waste disposal expenses. However, there are some drawbacks to producing hydrogen through photobiological processes. One of the challenges is the process's low efficiency, which limits the amount of hydrogen that can be generated. Furthermore, the process is presently not economically viable when compared to other methods of hydrogen production, such as steam methane reforming. In conclusion, photobiological hydrogen production is a promising technology with the potential to provide a sustainable and environmentally friendly source of hydrogen gas. However, more research is required to improve the process's efficiency and reduce its cost.

4. Comparison of hydrogen production technologies

Steam methane reforming (SMR) is the most popular technique for producing hydrogen, accounting for around 95% of global hydrogen production. The reaction of natural gas (methane) with steam yields hydrogen and carbon monoxide. A shift reaction is subsequently used to separate the hydrogen from the carbon monoxide. SMR is a mature technology that is now the most cost-effective method of creating hydrogen; yet, it raises certain environmental issues due to the release of greenhouse gases such as carbon dioxide [36,117].

The splitting of water into hydrogen and oxygen by an electric current is known as electrolysis [118]. Renewable energy sources such as wind, solar, and hydroelectric power can be used to power this process. In addition, anaerobic conditions are used to promote hydrogen synthesis in microorganisms [119]. This is accomplished by either cutting off the oxygen supply to the bacteria or purging the system with an inert gas such as nitrogen. For the production of hydrogen, under anaerobic circumstances, bacteria convert from producing oxygen to producing hydrogen gas, a process known as photosynthetic hydrogen production. The hydrogen gas is then collected and cleaned before being used. There are various advantages to producing hydrogen using photobiological processes. To begin with, the procedure is ecologically beneficial because it does not entail the use of fossil fuels. Second, the technique makes use of solar energy, which is plentiful and renewable. Finally, the technique uses wastewater or other waste streams as a source of nutrients, lowering waste disposal expenses. Photobiological processes employ photosynthetic microorganisms like algae to create hydrogen. Sunlight is used by these organisms to transform carbon dioxide and water into organic molecules and oxygen. These organisms can manufacture hydrogen in the absence of oxygen via a process known as photobiological hydrogen generation. Photobiological processes are still at the research and development stage, but they provide a potential technique for producing ecologically benign hydrogen [114,115].

Therefore, each technique of producing hydrogen has advantages and disadvantages. SMR is the most cost-effective technology, however, it produces greenhouse emissions. Although electrolysis is ecologically beneficial, it is nevertheless quite costly. Thermochemical and biological processes are still in the research and development phase, and commercialization is not yet a viable option. Photobiological processes are a potential method for producing ecologically acceptable hydrogen, however, they are still in the research and development stage. To address the growing demand for hydrogen fuel, additional research and development are needed to make these systems more efficient, cost-effective, and scalable.

5. Hydrogen storage technologies

5.1. *Compression*

Owing to its high energy content and low environmental effect, hydrogen is a viable fuel for a wide range of uses. Yet, one of the greatest obstacles to utilizing hydrogen as a fuel is its low density, which makes huge volumes difficult to store. Compression is a hydrogen storage technique that can assist alleviate this issue [120,121]. Compression is the process of compressing hydrogen gas to high pressures, often in the range of 350–700 bar, in order to enhance its density and lower the needed storage volume. This compressed hydrogen may be further stored as fuel in tanks or cylinders. Mechanical compression and cryogenic compression are the two basic kinds of hydrogen compression [122]. Mechanical compression is the mechanical compression of hydrogen gas using a compressor or pump. Cryogenic compression involves liquefying hydrogen gas by chilling it to an extremely low temperature, often below $-253\,^{\circ}C$, and then compressing the liquid hydrogen [123].

Mechanical compression and cryogenic compression both have advantages and downsides. Mechanical compression is less expensive and easier to run in general, but it consumes more energy and may generate heat that must be regulated. Cryogenic compression uses less energy and delivers better storage densities, but it is more complicated and expensive to run due to the requirement for cryogenic equipment. Overall, compression is a significant approach for hydrogen storage since it allows hydrogen to be used as a fuel in a range of applications [123,124].

This approach, however, is plagued by challenges and limitations. One key problem is preserving safety and dependability while attaining high compression ratios. Hydrogen is a highly reactive gas that can be difficult to confine and compress without leaking or posing other safety risks [125]. Nevertheless, compression devices can be costly and energy-intensive, limiting their general usage. Another difficulty is “boil-off,” which arises if compressed hydrogen is held for long periods. The compressed hydrogen can boil out as the temperature of the storage container rises, lowering the amount of stored hydrogen and thus posing safety risks [126].

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Notwithstanding these obstacles, compression remains a potential option for hydrogen storage, especially in applications requiring high energy density. Future research in this field is anticipated to focus on enhancing the safety, efficiency, and reliability of compression systems, as well as creating novel materials and methods for hydrogen storage and release. This might entail developing sophisticated compression systems that utilize renewable energy sources like solar or wind power, as well as novel hydrogen storage materials like metal hydrides or carbon nanotubes. Overall, the prospects for compression as a hydrogen storage strategy seem encouraging, but major research and development efforts will be required to overcome the existing problems and constraints [126–128].

5.2. *Liquefaction*

Liquefaction is a hydrogen storage process that includes chilling hydrogen gas to extremely low temperatures (−253 °C or −423 °F) till it condenses into a liquid. The liquid form of hydrogen is kept in specially built-containers that can survive the relatively low temperatures and high pressures necessary for storage. One of the benefits of liquefaction as a hydrogen storage technology is that it allows for substantial volume reduction, making it more effective for transit and storage [126]. For example, because gaseous hydrogen has a lower energy density than liquid hydrogen, it takes a larger volume to store the same amount of energy. Yet, there are several disadvantages to adopting liquefaction as a hydrogen storage technology. Cooling hydrogen to such low temperatures necessitates a substantial amount of energy, which may be costly and energy-intensive. Moreover, there may be difficulties with hydrogen boil-off and venting during storage, resulting in hydrogen losses and further safety concerns [126,129].

5.3. *Adsorption*

The adsorption technique for hydrogen storage entails the use of a substance to adsorb or store hydrogen molecules at low pressure. This is in contrast to standard high-pressure hydrogen storage technologies, which need the gas to be stored in high-pressure tanks. The storage media in adsorption-based hydrogen storage devices is a porous substance. The material has a vast surface area and is capable of absorbing significant amounts of hydrogen gas under low pressures. Through weak van der Waals forces or other interactions, hydrogen molecules are retained within the pores of the material. The hydrogen molecules are released from the substance when the pressure or temperature is decreased [130,131]. A variety of materials, including activated carbon, metal-organic frameworks (MOFs), and zeolites, can be employed for adsorption-based hydrogen storage. Each material has distinct features, such as pore size and surface area, that make it appropriate for hydrogen storage under certain conditions [132].

Adsorption-based hydrogen storage has the potential to provide a greater volumetric energy density than standard high-pressure storage technologies. Because of the adsorbent material's large surface area, hydrogen may be held in a smaller volume. Furthermore, because adsorption-based systems may function at lower pressures, they may be safer than high-pressure systems [133]. However, there are certain disadvantages to adsorption-based hydrogen storage. One problem is the requirement for materials with large hydrogen storage capacities and excellent kinetics, which means they can adsorb and desorb hydrogen quickly. Another issue is the possibility of material deterioration over time, which might limit the system's storage capacity and efficiency. Despite these obstacles, adsorption-based hydrogen storage appears to be a promising alternative for storing hydrogen for fuel cell cars and other purposes. To solve the technological obstacles and make these systems economically viable, more research and development will be required [125,134].

5.4. *Metal hydrides*

Metal hydrides are substances that are capable of holding hydrogen atoms through chemical bonding. These materials are being investigated for use in hydrogen storage because they have various benefits over other techniques of storage, such as compressed hydrogen gas or liquid hydrogen. Metal hydrides have the benefit of being able to store hydrogen at high densities, which means that a smaller volume of material can hold the same quantity of hydrogen as a greater volume of compressed gas or liquid [135,136]. This makes metal hydrides more suitable for use in automobiles and other applications with limited space [137]. Metal hydrides also have the benefit of being able to release hydrogen at low temperatures and pressures. This is significant because it minimizes the amount of energy and infrastructure required for hydrogen storage and distribution [138]. Furthermore, because metal hydrides are more stable and less prone to leak or explode, they are safer to handle and carry than compressed gas or liquid hydrogen [120,139].

Metal hydrides of many forms are being studied for hydrogen storage, which includes complex metal hydrides, lighter metal hydrides, and intermetallic hydrides. Compounds containing a metal ion and a ligand capable of forming bonds with hydrogen atoms are known as complex metal hydrides. Light metal hydrides are materials that contain light metals that may form stable hydrides, such as magnesium [51,140]. Intermetallic hydrides are compounds composed of two or more metals capable of forming intermetallic hydrides. Before metal hydrides may be employed economically for hydrogen storage, various obstacles must be addressed. Some metal hydrides, for example, need high temperatures or pressures to release hydrogen, which may be energy-intensive and costly. Furthermore, some metal hydrides deteriorate with time, decreasing their capacity to hold hydrogen [141,142].

Despite these obstacles, metal hydrides are a potential hydrogen storage technique, and research in this field is ongoing. Metal hydrides may play an essential role in enabling the widespread use of hydrogen as a fuel as the need for renewable energy sources develops.

5.5. *Chemical hydrides*

Chemical hydrides are substances that, by chemical bonding, may store hydrogen. They are a viable hydrogen storage technology because of their significant volumetric energy

density and ability to release hydrogen on demand. Metal hydrides, as well as complex hydrides, are the two types of chemical hydrides. Metal hydrides are generated when a metal reacts with hydrogen. Magnesium hydride, sodium borohydride, and lithium hydride, and are a few examples. Metal hydrides possess elevated gravimetric and volumetric hydrogen densities, which makes them appealing for space-constrained applications [143]. However, they often require high temperatures to release hydrogen, limiting their practical application. Complex hydrides are created by combining a metal with a complex anion that contains hydrogen. Sodium alanate, lithium borohydride, and sodium borohydride are a few examples. Complex hydrides, unlike metal hydrides, often release hydrogen at lower temperatures and can be refilled with hydrogen more easily. They have lesser hydrogen storage capabilities than metal hydrides, though [144,145].

One of the benefits of chemical hydrides is their capacity to release hydrogen on demand. This renders them particularly appealing for use in fuel cells, which require a constant supply of hydrogen. Chemical hydrides also have the ability to store hydrogen in a safe and compact manner, which is necessary for many applications [146,147]. However, various obstacles must be addressed before chemical hydrides can become a viable hydrogen storage technique. High temperatures or pressures are required to release hydrogen, as are delayed hydrogen release kinetics and the usage of poisonous or costly materials. Researchers are working hard to overcome these issues by developing new materials as well as processing techniques [148–150].

In conclusion, chemical hydrides are a viable hydrogen storage technique due to their high energy density and capacity to release hydrogen on demand. However, further study is required to address the difficulties connected with their utilization and increase their applicability for real-world applications.

5.6. *Comparison of technologies*

Hydrogen is seen as a viable energy carrier owing to its high energy content, availability, and promise for minimal emissions. However, its usage as a fuel necessitates efficient and secure storage systems. Here is a comparison of five hydrogen storage systems (as shown in Fig. 6), namely compression, liquefaction, adsorption, metal hydrides, and chemical hydrides, based on their future possibilities and challenges.

Compression is the process of pressurizing hydrogen gas to store it at high pressures in tanks. It is a well-established and frequently utilized technology in the industry, with a large storage capacity. However, it does face significant obstacles, such as the requirement for specialized tanks and compressors, high energy consumption during compression, and safety issues due to the high pressure. Recent advancements in compression technology have resulted in the creation of more efficient and compact compressors. Furthermore, the adoption of modern materials in tank construction has enhanced storage capacity while decreasing tank weight. Despite advancements, compression still necessitates a large energy input for storage and transportation, and compressors and tanks can be expensive. Furthermore, high pressure can be dangerous, and the possibility of leakage must be properly monitored [120,125].

Liquefaction is the process of cooling hydrogen gas to a level below its boiling point (−253 °C) in order to transform it into a liquid state for storage. It has a great storage density, but it takes a lot of energy to keep the liquid form cold and stable. Recent advances in liquefaction technology have resulted in the creation of more efficient cryogenic systems that use less energy to chill and keep hydrogen liquid. Furthermore, the adoption of better insulating materials has aided in lowering the boil-off rate of stored hydrogen. Liquefaction demands a large amount of energy, which can compensate for the high energy content of the stored hydrogen. Furthermore, the high expense of cryogenic systems and the requirement for specialized tanks may be a hurdle to general implementation [126,129].

Adsorption is the process of storing hydrogen in a solid substance such as activated carbon or metal-organic frameworks (MOFs) with large surface areas that can adsorb hydrogen molecules. It provides low-pressure storage and has the potential for large storage capacity. Recent advances in MOF synthesis and engineering have resulted in the creation of materials with increased hydrogen absorption capability and stability. Furthermore, the advancement of sophisticated manufacturing processes has aided in the reduction of MOF costs. Adsorption necessitates the use of a substance with a large surface area for storage, limiting storage capacity. Furthermore, the adsorption-desorption process can be sluggish and energy-intensive, making practical use difficult [131,134].

Metal hydrides include the storage of hydrogen in a solid substance that may chemically link with hydrogen atoms. It provides a secure and reversible storage solution with the potential for large storage capacity. Recent metal hydride research has concentrated on the creation of novel materials with increased hydrogen storage capacity and reversibility. Furthermore, the utilization of improved production processes has assisted in lowering the cost of metal hydrides. Metal hydrides can be sensitive to temperature and pressure fluctuations, limiting their practical application. Furthermore, some metal hydrides might be unstable or need high temperatures to release hydrogen, limiting their effectiveness [120,141,147].

Chemical hydrides include the storage of hydrogen in a solid substance that can release hydrogen when it reacts with water or another chemical agent. It provides a secure and compact storage solution with the potential for large storage capacity. New materials with enhanced hydrogen release kinetics and stability have been developed as a result of recent advances in chemical hydride synthesis and engineering. Furthermore, the utilization of sophisticated production processes has assisted in lowering the cost of chemical hydrides. Chemical hydrides have a limited capacity for storing hydrogen, and their interaction with water can yield undesirable by-products that must be regulated. Furthermore, the reaction kinetics might be sluggish, and the requirement for specialized handling techniques can limit their practical application [120,147].

Each of these hydrogen storage systems has advantages and disadvantages. Adsorption, metal hydrides, and chemical hydrides provide lower-pressure and safer storage alternatives with variable degrees of storage capacity, whereas

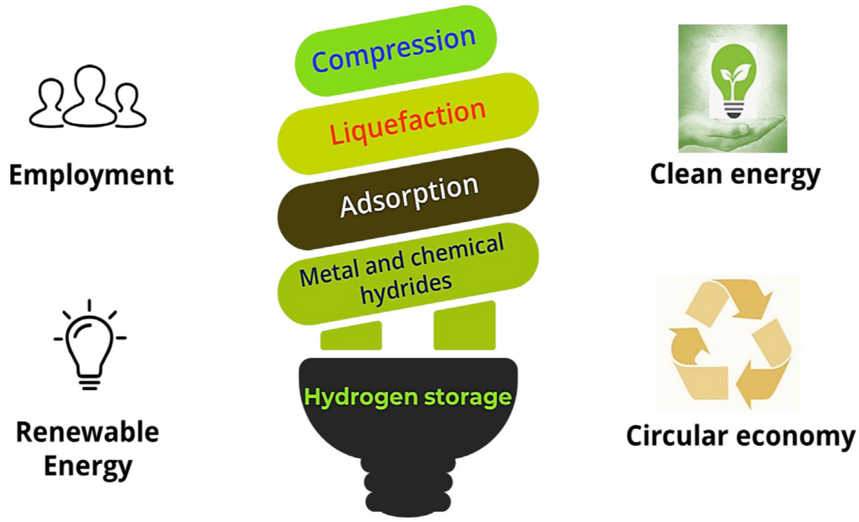

Fig. 6 – Main technologies for hydrogen storage.

compression and liquefaction offer large storage densities but need substantial energy input. Advances in materials science and engineering, on the other hand, are constantly improving these technologies, and a combination of various storage systems may be the most feasible approach for the practical and widespread usage of hydrogen as a fuel.

6. Hydrogen utilization technologies

Hydrogen has been highlighted as a possible alternative fuel that can substitute fossil fuels due to its high energy content, adaptability, and clean-burning features. In the energy sector, hydrogen may be utilized to generate electricity and heat in a variety of ways. The several uses of hydrogen are depicted in Fig. 7. Here are several methods for using hydrogen.

Fuel cells are electrochemical devices that transform the chemical energy of hydrogen straight into electrical energy. Fuel cells are extremely efficient and can generate power with zero pollution. Fuel cells can be employed in transportation, fixed power generation, and portable applications. Hydrogen may be consumed in combustion engines, turbines, and boilers to create heat and power. Hydrogen combustion generates just water as a byproduct, making it a clean-burning fuel. Nevertheless, combustion engines tend to be less efficient than fuel cells, and hydrogen's high flame speed might pose safety concerns [50,58].

Metal hydrides, which are compounds of hydrogen and metal, can be used to store hydrogen. Metal hydrides have a high density of hydrogen storage and may release hydrogen on demand. Hydride storage is appropriate for stationary power generating and transportation applications where space and weight are important considerations. To minimize emissions, hydrogen can be combined with natural gas or other fossil fuels. Hydrogen-natural gas blends can reduce carbon emissions and enhance fuel efficiency in natural gas-fired power plants and pipelines. The quantity of hydrogen that may be mixed, however, is restricted by current infrastructure and equipment. Electrolysis is a method of splitting water into hydrogen and oxygen that employs electricity. To create green hydrogen, electrolysis can be fueled by renewable energy sources such as solar, wind, or hydropower. Because electrolysis can produce hydrogen on-site, it is appropriate for small-scale applications such as fueling stations and distant power generation [141,151].

To summarize, hydrogen may be used in a variety of energy applications, including fuel cells, combustion, hydride storage, blending, and electrolysis. Each approach has advantages and disadvantages, and the technology chosen for hydrogen utilization is determined by the unique application and needs.

6.1. *Fuel cells*

A fuel cell is a form of an electrochemical cell that transforms the chemical energy of a fuel and an oxidant into electrical energy [152]. The anode, cathode, and electrolyte are the three essential components of a fuel cell. The negative electrode is the anode, and it is where the fuel (typically hydrogen) enters the cell. The positive electrode is the cathode, and it is where

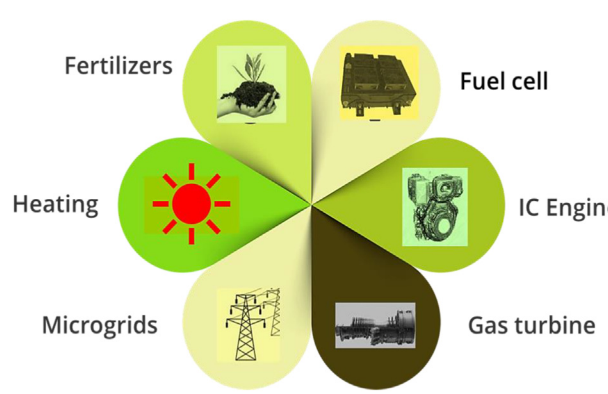

Fig. 7 – Applications of hydrogen.

the oxidant (typically oxygen) enters the cell [50,58]. The material that permits ions to move between the anode and cathode is known as the electrolyte. When the fuel and oxidant are delivered to the anode and cathode, a chemical reaction happens that produces electricity. At the anode, the fuel (typically hydrogen) is oxidized, creating protons and electrons. However, combustion engines are less efficient than fuel cells, and hydrogen's high flame speed might pose safety concerns [33,153].

The electrons are pushed to proceed to the cathode through an external circuit, where they react with the oxidant (typically oxygen) and protons to generate water. The fuel cell's electricity may power a wide range of devices, from small gadgets to ships and even homes [154]. Because the sole result of the chemical reaction in a fuel cell is water, it is frequently regarded as a more ecologically friendly alternative to typical combustion engines. Among the several types of fuel cells are polymer electrolyte membrane (PEM) fuel cells, solid oxide fuel cells, and molten carbonate fuel cells [155]. Depending on the application, each type of fuel cell has its qualities and advantages. Overall, fuel cell technology has the potential to transform how we create and consume energy by providing a clean and efficient alternative to existing fossil fuels [156–158].

One of the most significant problems is the high expense of developing and deploying fuel cell technology. Currently, fuel cell devices are more costly than conventional combustion engines or similar energy sources, and the infrastructure needed to support them is still in its early stages [159]. Furthermore, the cost of manufacturing hydrogen, which is frequently used as a fuel for fuel cells, remains rather expensive. Another issue is hydrogen storage and transit. Hydrogen is a highly flammable gas that can be hazardous to store and transport. While breakthroughs in safer and more efficient hydrogen storage and transportation systems have been achieved, these technologies are still in the early phases of research [159,160].

There are additional technical issues about the durability and dependability of fuel cell systems. Some fuel cell components, such as the membrane in a PEM fuel cell, are susceptible to environmental factors and deteriorate over time. It will be vital to ensure the lifetime and dependability of fuel cell systems if they are to be widely used [161]. Despite these obstacles, fuel cell technology has some exciting prospects. As technology advances and production costs fall, fuel cells may become a more realistic choice for a variety of uses, including transportation, home, and commercial power generation, and possibly space exploration.

Advances in hydrogen generation and storage technologies, as well as the development of novel fuel cell materials and designs, might potentially aid in the resolution of some of the technical issues confronting fuel cell systems. Furthermore, as governments and companies continue to priorities the shift to cleaner energy sources, demand for fuel cell technology is expected to rise, spurring additional research and development and promoting the creation of accompanying infrastructure. While there will undoubtedly be obstacles to overcome, the prospects for fuel cell technology are excellent, and the technology has the potential to play a big part in the transition to a more sustainable energy future [162,163].

6.2. *Internal combustion engines*

Internal combustion engines (ICEs) fueled by hydrogen are a potential technology for the automobile industry since they provide an ecologically benign alternative to typical gasoline-driven engines. Instead of petrol or diesel, hydrogen petrol is utilized as a fuel in a hydrogen-powered ICE [164,165]. The hydrogen is kept in the vehicle's tank before being injected into the engine's combustion chamber, where it combines with air [166,167]. The mixture is then ignited by a spark plug, resulting in a controlled explosion that pushes the engine's pistons, providing mechanical energy that propels the vehicle [26,168]. One of the primary advantages of hydrogen-powered ICEs is that they emit no greenhouse gases because the sole consequence of combustion is water vapor. As a result, they are a more appealing alternative to typical gasoline-powered engines, which contribute to air pollution and global warming. Furthermore, because hydrogen has a larger energy content per unit weight than gasoline, hydrogen-powered ICEs have the potential to be more efficient than gasoline-powered engines [168,169]. This means that a lower concentration of hydrogen may create the same amount of energy as a higher concentration of petrol [170,171]. However, there are certain obstacles to the general use of hydrogen-powered ICEs [172,173]. One of the most significant obstacles is a lack of infrastructure for hydrogen fueling stations. There are currently extremely few hydrogen fueling facilities, limiting the viability of hydrogen-powered ICEs for long-distance travel. Another difficulty is the high expense of manufacturing and storing hydrogen. Hydrogen is normally created via an electrolysis method, which takes a substantial amount of power. Furthermore, hydrogen must be kept under high pressure or at extremely low temperatures, which necessitates specialized equipment that might be costly [174,175].

Finally, hydrogen-powered internal combustion engines represent a potential technology for the automobile sector since they offer a zero-emission alternative to typical gasoline-powered engines. However, the absence of infrastructure for hydrogen filling stations, as well as the expense of manufacturing and storing hydrogen, are obstacles that must be overcome before broad adoption can take place.

There are various obstacles involved with scaling up hydrogen-powered internal combustion engine (ICE) technology that must be overcome before it can be widely used. Among these difficulties are [175–177].

- Infrastructure: The absence of hydrogen fueling stations is a significant barrier to scaling up this technology. To meet the rising demand for hydrogen fuel, more hydrogen fueling stations must be created.
- Cost: The cost of creating and storing hydrogen is currently greater than the cost of traditional fossil fuels, making this technology difficult to compete in the market. Lowering production and storage costs is critical for scalability.
- Safety: Because hydrogen is a very combustible gas, there are worries about utilizing it as a fuel. To ensure the safe usage of hydrogen-powered ICEs, certain safety precautions must be implemented.

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- Durability: Because hydrogen combustion is more corrosive than typical fuels, it might reduce the life of engine components. It is critical to develop materials that can survive the corrosive effects of hydrogen to scale up this technology.

Despite these obstacles, there are numerous possible avenues for the expansion of hydrogen-powered ICEs. Among these prospects are [160,175,178].

- Benefits to the environment: Hydrogen-powered ICEs are a zero-emission alternative to typical fossil-fuel-powered automobiles. As a result, they are an appealing choice for lowering greenhouse gas emissions and mitigating climate change.
- Energy security: Because hydrogen can be generated in the United States, it can lessen dependency on foreign oil and boost energy security.
- Efficiency: Because hydrogen has a larger energy content per unit weight than traditional fuels, hydrogen-powered ICEs may be more efficient.
- Compatibility: Because hydrogen can be utilized in current internal combustion engines, it can be easily incorporated into existing vehicle fleets.

Finally, scaling up hydrogen-powered ICE technology has the potential to reduce greenhouse gas emissions, improve energy security, and increase efficiency. However, solving infrastructure, cost, safety, and durability issues is critical for wider implementation.

6.3. Gas turbines

Hydrogen-powered gas turbines are a potential power production technology because they provide an ecologically beneficial alternative to typical fossil-fuel-based power generation [179]. Hydrogen gas is burnt in a combustion chamber to produce hot gas, which powers a turbine to generate mechanical energy in a hydrogen-powered gas turbine [180,181]. A generator then converts mechanical energy into electrical energy. Because hydrogen combustion generates just water vapor, it is an appealing alternative to standard fossil fuels, which emit greenhouse gases and contribute to climate change [182]. Moreover, hydrogen provides more energy per unit weight than traditional fossil fuels, a smaller amount of hydrogen may create the same amount of energy as a bigger amount of fossil fuels. Furthermore, hydrogen combustion creates high temperatures, which boosts the turbine's efficiency [183].

The versatility of hydrogen-powered gas turbines is another advantage. They can be used to supply both base-load power (electricity that is regularly required to satisfy a minimal demand) and peak-load power (power that is required to meet a rapid rise in demand). This makes them useful for a variety of applications, including grid power generation as well as industrial and commercial use [184]. However, there are certain obstacles to the widespread use of hydrogen-powered gas turbines. One of the most significant obstacles is a lack of infrastructure for hydrogen generation and delivery. Hydrogen must be created via an electrolysis process, which takes a substantial quantity of power. Furthermore, hydrogen must be transferred to the power plant, which necessitates the use of specialized equipment, which may be costly [185,186].

Another issue is the high expense of producing hydrogen. At the moment, the cost of manufacturing hydrogen exceeds that of conventional fossil fuels. This makes competing in the market for hydrogen-powered gas turbines challenging. Lowering the cost of producing hydrogen is critical for its broad adoption. Finally, hydrogen-powered gas turbines are a potential power-generating technology since they give an ecologically beneficial alternative to traditional fossil fuel-based power generation. Nevertheless, a lack of infrastructure for hydrogen production and delivery, as well as the expense of hydrogen generation, are obstacles that must be overcome before it can be widely used [187,188].

There are a number of issues involved with scaling up hydrogen-powered gas turbine technology that must be overcome before it can be widely used. Among these difficulties are [182,189,190].

- Infrastructure: A key barrier to scaling up this technology is a shortage of hydrogen manufacturing and transportation infrastructure. To meet the rising demand for hydrogen, more hydrogen production facilities and transportation networks must be created.
- Cost: The cost of manufacturing hydrogen by electrolysis is currently greater than that of traditional fossil fuels, making this technology difficult to compete in the market. Lowering production costs is critical for scalability.
- Safety: Because hydrogen is a highly combustible gas, there are issues concerning its production, storage, and transportation. To guarantee the safe operation of hydrogen-powered gas turbines, proper safety measures must be implemented.
- Durability: Because hydrogen combustion is more corrosive than typical fuels, it might reduce the life of gas turbine components. It is critical to develop materials that can survive the corrosive effects of hydrogen in order to scale up this technology.

Despite these obstacles, there are numerous possible avenues for scaling up hydrogen-powered gas turbine technology. Among these prospects are [191–193].

- Benefits to the environment: Hydrogen-powered gas turbines provide a zero-emission alternative to typical fossil-fuel-based power generating. As a result, they are an appealing choice for lowering greenhouse gas emissions and mitigating climate change.
- Energy security: Because hydrogen can be generated in the United States, it can lessen dependency on foreign oil and boost energy security.
- Flexibility: Because hydrogen-powered gas turbines can produce both base-load and peak-load power, they are appropriate for a wide range of applications, including grid power generation as well as industrial and commercial use.
- High Efficiency: High temperatures produced by hydrogen combustion boost the efficiency of gas turbines. As a result, they may be more efficient than traditional fossil-fuel-based power generation.

Finally, scaling up hydrogen-powered gas turbine technology has the potential to reduce greenhouse gas emissions, improve energy security, and increase efficiency. However, solving infrastructure, cost, safety, and durability issues is critical for wider implementation. Hydrogen-powered gas turbines are a potential power-generating technology since they give an ecologically beneficial alternative to traditional fossil fuel-based power generation. Nevertheless, a lack of infrastructure for hydrogen production and delivery, as well as the expense of hydrogen generation, are obstacles that must be overcome before it can be widely used.

6.4. *Other applications*

Hydrogen-based energy storage is a possible approach for integrating renewable energy sources into the grid, such as wind and solar power [194]. Using an electrolyze, hydrogen may be created from renewable energy sources and stored for later use in fuel cells or combustion engines to generate power. The creation of hydrogen using water electrolysis is the first step in the process of hydrogen-based energy storage. An electrical current is used in this technique to split water into hydrogen and oxygen, which are then kept separately. The hydrogen can then be compressed and stored in tanks or pipes for future use. When power is required, the stored hydrogen may be utilized in a fuel cell to create it. To generate electricity, fuel cells employ a chemical interaction between hydrogen and oxygen, with the only waste being water and heat. As a result, hydrogen is a very clean and efficient energy storage alternative [26,190,195].

Another method of using stored hydrogen is burning. Hydrogen is used in a combustion engine to create energy in this process. While combustion emits some pollutants, it is still a more environmentally friendly alternative to typical fossil fuels [196]. One advantage of hydrogen-based energy storage is its adaptability. Hydrogen may be created utilizing intermittent and variable renewable energy sources such as wind and solar power [197]. This implies that extra energy created during high-production periods may be saved for use during low-production periods [198,199]. However, there are several drawbacks to using hydrogen for energy storage. The cost of manufacturing and storage is one of the most significant difficulties. Currently, the cost of creating hydrogen by electrolysis is relatively expensive, as is the cost of storing it. Another difficulty is the existing lack of infrastructure for hydrogen transportation and distribution [200]. Overall, hydrogen-based energy storage has the potential to significantly contribute to the transition to a more sustainable and renewable energy future [201,202]. Further study and development, however, are required to overcome the existing hurdles and make this technology more readily available and cost-effective [203].

Hydrogen-based microgrids are a new technology that can supply communities and companies with a stable and sustainable source of electricity [204,205]. A microgrid is a localized power system that may run independently of the main power grid and is frequently fueled by renewable energy sources such as solar, wind, or hydropower. Hydrogen-based microgrids employ hydrogen as an energy carrier since it is renewable and can be stored for later use. The main idea behind a hydrogen-based microgrid is that renewable energy sources like solar or wind are utilized to generate power, which is then used to manufacture hydrogen via electrolysis. After that, the hydrogen is kept in tanks or other storage systems and may be utilized to create energy using fuel cells or combustion engines. The advantage of this strategy is that hydrogen can be stored for longer periods than electricity, allowing energy to be used when needed, such as when renewable energy supply is low or energy demand is high [206,207]. Microgrids powered by hydrogen can also be utilized as a backup power supply for important infrastructure such as hospitals, data centers, and military facilities. Without relying on the main electrical grid, hydrogen can provide a stable supply of power during emergencies or power outages in several applications [208]. There may also be advantages for rural settlements that are not linked to the main power grid. Hydrogen-powered microgrids can provide a low-cost, long-term energy supply, lowering dependency on fossil fuels and enhancing energy security.

However, there are several drawbacks to hydrogen-based microgrids, such as infrastructure costs and the availability of renewable energy sources. Furthermore, because hydrogen is a highly combustible gas, there are safety risks related to its storage and handling. Overall, hydrogen-based microgrids are a viable option for renewable energy systems, with the ability to provide communities and companies with a stable, sustainable, and inexpensive source of electricity.

7. Environmental and economic assessment

Hydrogen-based renewable energy systems have been offered as a possible method for reducing greenhouse gas emissions and transitioning to a low-carbon energy future. An environmental and economic study is required to determine the feasibility and advantages of such systems.

7.1. *Environmental evaluation*

The environmental impact of a hydrogen-based renewable energy system should be considered throughout its whole lifespan, from hydrogen generation through end consumption. This evaluation should include the following kinds of environmental impacts [209–211].

- Emissions of greenhouse gases: Hydrogen-based renewable energy systems are predicted to emit fewer greenhouse gases than fossil-fuel-based energy systems. However, emissions connected with hydrogen generation, transportation, and storage must also be addressed.
- Water consumption: The creation of hydrogen necessitates the use of a huge volume of water. As a result, the environmental evaluation should consider the system's influence on water resources.
- Land usage: The land use needs for hydrogen generation and storage should be assessed to ensure that they do not result in habitat degradation or biodiversity loss.
- Air pollution: The possibility of air pollution from hydrogen generation and transportation should also be considered.

7.2. Economic analysis

The economic assessment of a hydrogen-based renewable energy system should compare the system's costs and advantages to alternative energy sources. The following things should be taken into account [212–215].

- Capital expenses: To determine the system's economic viability, the capital costs related to hydrogen generation, storage, and transportation should be assessed.
- Running expenses: The system's running costs, including maintenance and labor costs, should be assessed to establish the system's long-term economic feasibility.
- Income generation: The potential income production from the sale of hydrogen or energy generated from hydrogen should be assessed to estimate the system's economic benefits.
- Externalities: Any externalities connected with the system, such as the cost of carbon emissions and the cost of environmental damages, should be considered in the economic evaluation.

  Overall, determining the viability and advantages of a hydrogen-based renewable energy system requires a full environmental and economic examination. These evaluations can provide policymakers and investors with the knowledge they need to make educated decisions concerning the development and deployment of these systems.

7.3. Life cycle assessment

The creation of hydrogen is the first step in the life cycle of a hydrogen-based renewable energy system. Hydrogen may be created using a variety of ways, including electrolysis, reforming, and biomass gasification. Electrolysis includes utilizing electricity to divide water molecules into hydrogen and oxygen, whereas reformation requires reacting hydrocarbons with steam to make hydrogen. In contrast, biomass gasification involves heating organic materials to generate a gas that may be utilized to make hydrogen [190]. LCA may be used to examine the environmental implications of each of these strategies. Electrolysis, for example, may be fueled by renewable energy sources such as solar or wind power, making it a sustainable alternative. However, reforming emits greenhouse gases, and the sustainability of biomass gasification is dependent on the sustainability of the organic materials utilized [216,217].

Once created, hydrogen must be stored and delivered to its final destination. Hydrogen storage and distribution require energy and resources as well, and LCA may assist in estimating the environmental effect of these operations. Hydrogen, for example, may be kept as a gas or a liquid, and each storage option has various environmental implications. Varied modes of transportation, such as pipelines or tankers, have varied environmental implications. Finally, the use of hydrogen as an energy source generates emissions and waste, which must also be included in LCA. Hydrogen may be used to create energy in fuel cells or to power automobiles in combustion engines. As byproducts, fuel cells emit water and heat, whereas combustion engines emit nitrogen oxides and particulate particles [218,219].

We can find areas for improvement and strive towards a more sustainable energy future by completing a full LCA of a hydrogen-based renewable energy system. LCA can assist us in making educated judgments regarding which hydrogen production and storage systems are the most sustainable, as well as how to reduce the environmental effect of hydrogen use.

7.4. Technological readiness level

Renewable energy systems based on hydrogen are gaining popularity as a potential substitute for traditional fossil fuels. The Technological Readiness Level (TRL) is a metric that analyses a technology's maturity, with levels ranging from 1 (basic research) to 9 (commercial implementation). TRL for hydrogen-based renewable energy systems is high, suggesting that the technology is robust and mature. Hydrogen generation is the initial phase of a hydrogen-based renewable energy system. Hydrogen may be created via electrolysis or other ways from renewable sources such as wind, sun, and hydropower. Electrolysis is a well-established process that has been used in industry for decades to split water into hydrogen and oxygen by employing an electrical current. Large-scale commercial systems are already in operation, confirming the technology's maturity [220–222].

The next stage is to store and transfer hydrogen. Hydrogen is an extremely light and highly combustible gas that must be handled and stored with care. Hydrogen storage and transportation technologies, on the other hand, are already well-developed and established. Hydrogen can be kept in compressed gas cylinders or liquefied for transport, both of which are used in industry. Finally, hydrogen may be utilized to create power in fuel cells or as a clean fuel for transportation. Fuel cells are currently commercially accessible and utilized in many applications such as backup power systems and cars [223,224]. Commercially available hydrogen-powered vehicles include automobiles, buses, ships, and trucks. Despite the high TRL of hydrogen-based renewable energy systems, there are still obstacles to overcome. Improving the efficiency and cost-effectiveness of hydrogen generation, storage, and transportation is a big problem. Even if these technologies are developed, they might still be costly and inefficient when compared to traditional fossil fuels. Another problem is improving the longevity and dependability of fuel cells, which can be susceptible to impurities and require maintenance [225–227].

Finally, hydrogen-based renewable energy systems have achieved a high TRL, suggesting that the technology is well-developed and mature. Further research and development, however, are required to increase efficiency, cost-effectiveness, and dependability. Hydrogen-based renewable energy systems have the potential to become a competitive and sustainable alternative to existing fossil fuels with ongoing investment and innovation.

8. Market and policy trends

Hydrogen energy is gaining popularity as a clean and sustainable form of energy. Several commercial and policy

dynamics have led to the rise of the hydrogen and renewable energy sector in recent years, especially after the COVID-19 pandemic [228]. As an economist, I will discuss some of these patterns below:

Government support: Many governments throughout the globe have seen the promise of hydrogen energy and are investing heavily in its development [229]. The European Union, for example, has developed a Hydrogen Strategy to develop a clean hydrogen economy and has planned to invest €40 billion in the industry over the next decade. Similarly, Japan has established a goal of creating a hydrogen society by 2050 and is offering subsidies and tax incentives to achieve this goal. Similarly, Japan has established a goal of becoming a hydrogen society by 2050 and is offering subsidies and tax advantages to firms that invest in hydrogen technology [230–232].

Increasing industrial demand: Hydrogen is a critical feedstock for a variety of industrial processes, including chemical synthesis, refining, and steel manufacture. As businesses seek methods to reduce their carbon footprint, there is a rising demand for clean hydrogen as an alternative to fossil fuels [233,234].

Fuel cell technology advancements: Fuel cell technology, which turns hydrogen into energy, is continuously developing and becoming more efficient. This is resulting in the development of novel hydrogen uses, such as transportation and stationary power production [59,225].

Cost reduction: As new technologies and production methods are discovered, the cost of creating hydrogen is gradually decreasing. In some uses, this makes hydrogen more competitive with fossil fuels [62,235].

Partnerships and collaborations: Companies along the hydrogen value chain are developing partnerships and collaborations to exchange information and skills and expedite the sector's development. Hydrogen producers, for example, are collaborating with car manufacturers to build hydrogen fuel cell vehicles, while utilities are working with hydrogen producers to develop new infrastructure [236,237].

In summary, the hydrogen energy sector is seeing considerable growth and development, fueled by government assistance, rising industrial demand, advancements in fuel cell technology, lower costs, and partnerships and collaborations across the value chain [238]. These patterns are predicted to persist in the future. These trends are projected to continue, making hydrogen an important participant in the transition to a more environmentally friendly energy future.

9. Public perception and acceptance

In recent years, there has been a surge of interest in hydrogen energy as a possible replacement for existing fossil fuels. The utilization of hydrogen as a renewable energy source has the potential to drastically cut greenhouse gas emissions and alleviate climate change consequences. However, public opinion and acceptability of hydrogen energy are still growing and vary based on a variety of factors including area, country, and culture [239,240]. Some nations, such as Japan, South Korea, and Germany, have been at the forefront of researching and adopting hydrogen energy technology, while others are just getting started. People's opinions towards hydrogen energy are impacted by a variety of issues, including environmental concerns, energy security, economic considerations, and scientific advances. One of the primary barriers to widespread hydrogen energy adoption is a lack of infrastructure to enable its usage, such as hydrogen refueling stations for automobiles. Furthermore, there is a widespread belief that hydrogen energy is too costly and that the technology is not yet developed enough to be dependable and safe [241,242].

Despite these obstacles, public knowledge and interest in hydrogen and renewable energy are expanding, and governments and corporations are making investments in its development and implementation, the investment policy and strategies in renewable energy could be clearly seen especially after the COVID-19 pandemic [243]. Hydrogen energy has the capability to become an important contributor to the world's energy mix and help reduce the impacts of climate change with sustained research and development and the deployment of infrastructure to enable its usage [244].

10. Challenges and opportunities

One of the primary issues confronting hydrogen energy developers is the high cost of creating and storing hydrogen. Currently, the cost of producing and storing hydrogen exceeds that of conventional fossil fuels [245]. As a result, researchers have a significant hurdle in lowering the cost of hydrogen generation and storage. Another issue is a shortage of infrastructure for hydrogen energy, such as hydrogen refueling stations and storage facilities. Researchers must concentrate on building and implementing the infrastructure required to enable the use of hydrogen energy [246]. Because hydrogen is a highly combustible gas, problems with its production, storage, and transportation must be addressed [247,248]. Researchers must create safe and dependable hydrogen handling methods and techniques. Hydrogen has a poor energy density when compared to typical fossil fuels. This implies that storing the same quantity of energy as traditional fuels takes up a lot of room. To solve this difficulty, researchers must focus on creating and enhancing the efficiency of hydrogen storage devices. Currently, hydrogen production is energy-intensive, and the process emits greenhouse gases. Researchers must create more efficient and ecologically friendly hydrogen production systems. Hydrogen is a highly reactive gas that can induce embrittlement and other types of deterioration in some materials. Researchers must concentrate on producing hydrogen-compatible materials that can endure the harsh circumstances connected with their production, storage, and usage [249,250]. A graphical representation of challenges and opportunities in this domain is illustrated in Fig. 8.

The opportunities in this domain are that hydrogen may be created utilizing renewable energy sources such as wind and solar power. This provides an opportunity to include renewable energy sources into the energy mix while lowering greenhouse gas emissions. Hydrogen fuel cell cars have the potential to replace traditional gasoline-powered automobiles, lowering greenhouse gas emissions while also improving air quality. Researchers may concentrate on creating and upgrading hydrogen fuel cell car technologies.

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Fig. 8 – Challenges and opportunities in the hydrogen sector.

Hydrogen may be utilized as an energy storage medium, allowing intermittent renewable energy sources to be integrated into the grid. Researchers might concentrate their efforts on creating and enhancing hydrogen storage technologies for use in energy storage applications. Hydrogen has the potential to replace fossil fuels in a variety of uses, including power production, heating, and transportation. Hydrogen has an opportunity to replace fossil fuels in a variety of uses, including power generation, heating, and transportation. This provides a chance to cut greenhouse gas emissions and prevent climate change consequences. Hydrogen may be utilized as a feedstock in a variety of sectors, including chemical and steel manufacturing. Researchers may concentrate on creating and enhancing hydrogen-based industrial technologies. Hydrogen energy is a very new topic and much more to be found and developed. By inventing novel technologies, techniques, and materials that can increase the use of hydrogen energy, researchers have the chance to innovate and make substantial contributions to the area [26,190,251].

11. Conclusion

This assessment looked at the current condition of the hydrogen energy system, the major technologies involved, its applications, and prospects. The following are the primary outcomes.

11.1. *Summary of key findings*

The following are the key findings of the review study:

Hydrogen energy has the potential to alter the global energy system while also helping to mitigate the effects of climate change.

Hydrogen energy systems confront significant and numerous obstacles, including concerns with storage, production, distribution, infrastructure, safety, and cost.

Overcoming these obstacles will need a concerted effort on the part of scholars, legislators, industry leaders, and the general public.

Innovative technologies such as enhanced electrolysis systems and solid-state hydrogen storage materials offer considerable potential in overcoming some of the issues confronting hydrogen energy.

The role of government policies and regulations in promoting the development and deployment of hydrogen energy systems will be important.

Adoption of hydrogen energy systems would necessitate considerable infrastructure expenditures, including the construction of hydrogen refueling stations and pipelines.

Public awareness and education are critical for dispelling myths and skepticism about hydrogen energy and supporting its wider use.

To fully realize the promise of hydrogen energy, the collaboration between several sectors such as transportation, electricity, and industry would be required.

To bring innovative technologies to market, researchers, businesses, and government agencies will need to work closely together to commercialize hydrogen energy systems.

Despite the difficulties that hydrogen energy systems face, the potential benefits of this clean and sustainable energy source make it a viable subject of future study and development.

11.2. *Implications for practice and policy*

To begin, the review article emphasizes hydrogen energy's enormous potential as a clean and sustainable energy source that may aid in mitigating the consequences of climate change. However, the broad use of hydrogen energy is still hampered by a number of technological and infrastructure difficulties that must be solved.

In view of these problems, authorities should consider investing in research and development to overcome these issues and encourage the use of hydrogen energy. This

involves assisting in the development of new technologies, infrastructure, and safety regulations to enable the safe and efficient production, storage, and transportation of hydrogen.

The use of regulations and incentives like tax breaks for businesses investing in hydrogen energy and grants for the construction of hydrogen infrastructure, particularly in places with a shortage of it, should be taken into consideration by policymakers.

The research study also advises practitioners to concentrate on creating affordable and environmentally friendly ways to produce hydrogen and building up the infrastructure needed for its delivery and usage. This entails the creation of new infrastructure, such as hydrogen refueling stations, and new technologies for producing and storing hydrogen.

To summarize, while hydrogen energy has the potential to be a game changer in the fight against climate change, its adoption is still hindered by a variety of technological and infrastructure constraints. To solve these problems and promote hydrogen energy as a clean and sustainable energy source for the future, policymakers and practitioners must work together.

11.3. Directions for future research

Efficiency and sustainability: Improving the efficiency and sustainability of hydrogen-generating systems is one area of future study. This involves the development of more efficient and cost-effective electrolysis methods that utilize renewable energy sources, as well as the development of novel catalysts for hydrogen synthesis from alternative sources such as biomass.

Storage and infrastructure: Developing new storage and infrastructure technologies for hydrogen energy systems is another area of future study. This entails creating lightweight, cost-effective, and safe hydrogen storage materials, as well as creating new infrastructure for hydrogen transportation and distribution, such as hydrogen refueling stations.

Safety and laws: The production, storage, and transportation of hydrogen must be done safely. As such, future research should concentrate on creating new safety standards, technologies, and laws.

Integration with other energy systems: Another area for future research is the integration of hydrogen energy systems with other energy systems like electricity and natural gas. This entails creating fresh hybrid energy systems that mix hydrogen with various other energy sources as well as brand-new technologies and methods that permit the integration of hydrogen with current energy systems.

Economic viability: future research should focus on increasing the economic feasibility of hydrogen energy systems. Developing innovative business models and funding methods to promote the development and deployment of hydrogen energy systems, as well as lowering the cost of producing and storing hydrogen, are all part of this effort.

To summarize, the field of hydrogen energy systems faces many challenges that must be overcome before it can fully realize its potential as a clean and sustainable energy source. Future research should concentrate on improving the efficiency, sustainability, safety, and economic feasibility of hydrogen energy systems, as well as developing novel storage, infrastructure, and integration technologies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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