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REVIEW ARTICLE

Underlying Developments in Hydrogen Production Technologies: Economic Aspects and Existent Challenges

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Abstract

The quest for a carbon–neutral energy future has positioned hydrogen as a pivotal player in global-sustainability efforts. This comprehensive review examines the transformative role of hydrogen in revolutionizing sustainable energy consumption. Hydrogen's high energy density, versatility, and minimal ecological footprint make it ideal for stabilizing the intermittent nature of renewable energy sources. This study evaluates the latest advancements in hydrogen production technologies, including advanced electrolysis, reforming strategies, and biologic processes, assessing their operational efficiencies and environmental impacts. In addition, it explores the strategic deployment of hydrogen in transportation, industrial processes, and electricity sectors, highlighting its potential to significantly reduce fossil-fuel dependence and mitigate climate change. The economic considerations and policy imperatives crucial for the global adoption and scaling of hydrogen storage systems are also discussed. This review underscores hydrogen's critical role in creating an eco-efficient and resilient energy infrastructure, advocating for an accelerated transition to hydrogen-based solutions to achieve a cleaner, greener planet.

Keywords Hydrogen · Energy storage · Environmental · Renewable energy

Introduction

The steep increase in energy demand and the urgent necessity to address climate change have emphasized the significance of discovering sustainable energy solutions [1]. Hydrogen, being a clean and adaptable energy carrier, has become a crucial factor in the shift toward a sustainable energy future. Hydrogen's ability to greatly decrease greenhouse-gas emissions, along with its wide range of uses in transportation, industry, and power generation, positions it as a fundamental element in global-sustainability initiatives [2]. Advancements in hydrogen production technologies have been notable, with each technology having its distinct advantages and drawbacks. The main techniques comprise steam methane reforming (SMR), water electrolysis, biologic processes, and gasification [3–6].

The most well-established and economically efficient method for producing large quantities of hydrogen is SMR. The process entails the catalytic conversion of methane and steam into hydrogen and carbon dioxide [7]. Although SMR is economically efficient and commonly employed, it heavily depends on non-renewable natural gas and produces substantial carbon dioxide emissions [8].

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This contributes to the climate crisis unless it is combined with carbon capture and storage (CCS) technologies. Electrolysis is the process of separating water into hydrogen and oxygen using an electric current [9]. If this method is powered by renewable energy sources like wind or solar power, it can generate green hydrogen. The main obstacle associated with electrolysis is its substantial operational expense, primarily attributed to the energy demand [10]. Nevertheless, the progress in electrolyzer technology and its integration with renewable energy sources is enhancing the feasibility of this approach.

Biologic techniques, such as dark fermentation and photofermentation, employ microorganisms to generate hydrogen from organic substances [11]. Although these methods are both environmentally friendly and sustainable, their current limitations include low production rates and high operational costs. Ongoing research is being conducted to improve the efficiency and scalability of these processes. Gasification is a process that transforms carbonaceous substances, like coal, biomass, or waste, into hydrogen and other gases [12]. This method can utilize a diverse array of feedstocks, which makes it highly versatile. Nevertheless, gasification necessitates substantial financial resources and results in the emission of carbon dioxide, thereby requiring the implementation of carbon capture and storage (CCS) to minimize its environmental consequences [13].

Hydrogen storage is a crucial aspect that demands careful consideration. The main techniques comprise compressed gas, liquid hydrogen, and solid-state storage [14]. Every method presents distinct technical and economic obstacles, including exorbitant expenses, energy inefficiencies, and safety considerations. Researchers are currently investigating advanced materials and innovative storage solutions to overcome these obstacles [15–18]. Notwithstanding the progress made, hydrogen production technologies encounter various constraints. The substantial obstacle that persists is the elevated production expenses, especially in the case of green hydrogen.

The efficiency of production methods varies, with numerous processes experiencing energy loss during conversion procedure [19]. Furthermore, the infrastructure required for producing, storing, and distributing hydrogen is currently not well-developed, which presents difficulties for widespread implementation [20]. To tackle these challenges, numerous inventive strategies are being suggested. Integrating hydrogen production with renewable energy sources can substantially decrease carbon emissions and operational expenses. Efficiency and cost reduction are anticipated to be improved through advancements in catalyst development for SMR and electrolysis [21]. Moreover, advancing durable and effective storage materials, such as metal hydrides and carbon-based materials, show potential for enhancing hydrogen storage capabilities.

Government policies and incentives heavily influence the promotion of hydrogen technologies [22]. Investments in research and development, financial support for the production of green hydrogen, and the creation of hydrogen infrastructure are crucial for expediting the shift toward a hydrogen-based economy [23]. Overall, although there have been notable advancements in hydrogen production and storage technologies, there are still various obstacles that need to be addressed. By prioritizing the examination of present technological patterns, addressing existing constraints, and investigating inventive methods, we can establish the foundation for hydrogen to assume a pivotal position in attaining a sustainable and resilient energy future.

This paper titled "Underlying Developments in Hydrogen Production Technologies: Economic Aspects and Existent Challenges" distinguishes itself from prior publications by employing a thorough and multifaceted analysis. This paper provides a comprehensive and all-encompassing review by incorporating economic analysis, addressing present challenges, adopting an interdisciplinary approach, highlighting hydrogen production technology, discussing policy and strategic implementation, and conducting a comparative analysis of production methods. This makes it a valuable asset for policymakers, industry stakeholders, and researchers, making a substantial contribution to the progress of hydrogen technologies and the pursuit of a sustainable energy future.

Production of Hydrogen

Hydrogen can be generated from a diverse range of feedstocks, including water, coal, natural gas, biomass, hydrogen sulfide, boron hydrides, and various others, utilizing thermal, electrolytic, or photolytic methodologies. The categorization of hydrogen production can be delineated into four primary pathways, namely renewable, non-renewable, nuclear, and biomass, as illustrated in Fig. 1 [24]. Hydrogen derived from diverse renewable energy sources possesses the capability to be efficiently transported and stored [25]. Electrolysis and hydrogen storage have been widely advocated as viable options for both short-term (a few days) and long-term electricity storage alternatives due to their notable attributes, such as a low self-discharge rate and a divergence in energy and power ratings [26]. Renewable hydrogen production typically involves using surplus renewable energy to power the electrolysis of water, splitting it into hydrogen and oxygen. This process is emissions-free, assuming the electricity used is from renewable sources. The hydrogen produced can be stored indefinitely, converted back to electricity, or used as fuel for vehicles or in industrial processes [27]. Non-renewable hydrogen production is mainly associated with extracting hydrogen from fossil fuels. The most common method is SMR, where methane from natural gas

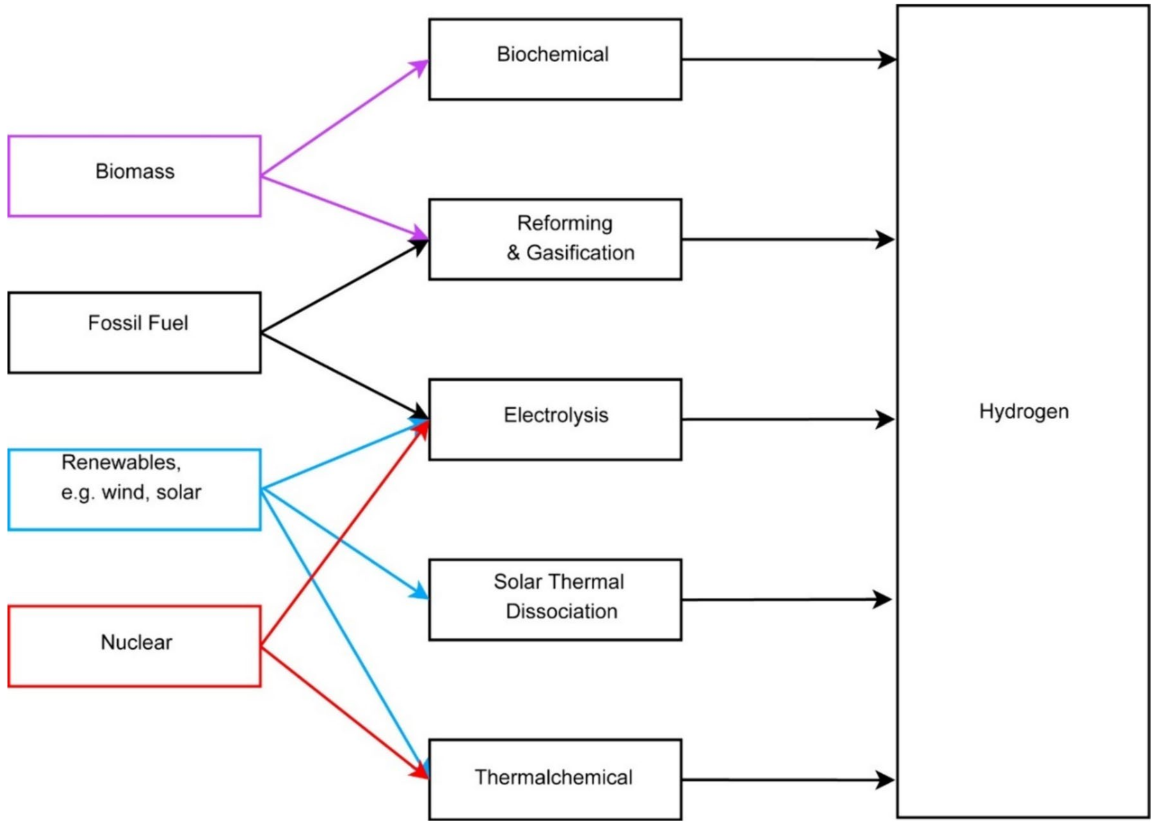

Fig. 1 The ways of hydrogen production. Reproduced with permission from Zhang et al. [24]. Copyright 2023, Elsevier

reacts with steam under high pressure and temperature to produce hydrogen, carbon monoxide, and a subsequent reaction to produce additional hydrogen and carbon dioxide. While this method is currently the most cost-effective, it is carbon-intensive unless combined with CCS technologies [28]. Nuclear energy can produce high-temperature heat for thermochemical water splitting or to provide electricity for electrolysis, offering a low-carbon hydrogen production route. High-temperature electrolysis can be more efficient than traditional methods due to the additional heat input [29]. Hydrogen production from biomass involves the gasification or pyrolysis of organic material to produce syngas (a mixture of hydrogen, carbon monoxide, and carbon dioxide), which is then processed to separate hydrogen. This method can be considered carbon–neutral if the biomass is sourced sustainably and the carbon dioxide produced is captured and stored [30]. Once produced, hydrogen serves as a versatile storage medium, allowing for the storage of large amounts of energy over long periods with minimal losses. It can be stored as a compressed gas, a cryogenic liquid, within chemical compounds, or in underground caverns, offering flexible options depending on the application and scale. Hydrogen is particularly advantageous for long-term energy storage, providing a buffer for seasonal fluctuations in energy supply and demand. This versatility is complemented by the ability to transport hydrogen over long distances, either through pipelines or in containers, thus enabling regional and global energy trade. However, the challenges of high production costs, efficiency improvements, and the development of infrastructure still need to be addressed. Looking ahead, the scalability of hydrogen storage, coupled with advancements in technologies like power-to-gas systems and novel transport methods, positions hydrogen as a key player in future energy landscape, with the potential to significantly impact how we store and use renewable energy.

Steam Methane Reforming

The distinction between reforming and gasification, as described in the literature, lies in the inherent characteristics of the fuel being utilized [31]. Gasification is a process that involves the conversion of solid fuels, such as coal, biomass, or solid waste, into hydrogen gas or synthesis gas, which is a mixture of hydrogen and carbon monoxide. On the other hand, reforming refers to the utilization of fluid fuel, whether in a gaseous or liquid state, to produce synthesis gas. The simplified net reaction for the steam reforming and steam-gasification process can be written as follows:

$$C_xH_y + xH_2O \overset{\text{High Temperature}}{\longrightarrow} \left(\frac{y}{2} + x\right)H_2 + xCO \quad (1)$$

The carbon monoxide generated by this chemical reaction has the potential to be converted into hydrogen gas by the catalytic water–gas shift reaction, which occurs at a reduced temperature, as depicted in Eq. (2). The process of separating and eliminating carbon dioxide from the resulting H_2 product, together with any residual contaminants such as nitrogen, methane, and carbon monoxide, can be undertaken.

$$CO + H_2O \rightarrow CO + H_2 \quad (2)$$

SMR is widely recognized as the predominant and readily accessible method utilized for large-scale hydrogen synthesis in commercial applications. The process involves the catalytic conversion of light hydrocarbons, including but not limited to natural gas, propane, butane, naphtha, biogas, or landfill gas, through the utilization of steam. The reforming of natural gas accounts for approximately 50% of the worldwide hydrogen supply [32]. The natural gas undergoes a desulphurization process facilitated by a catalyst to eliminate Sulpfur, which serves as the primary catalyst inhibitor. Subsequently, at conditions of elevated temperature ranging from 700 to 1100 °C and a typical pressure of 3 to 25 atmospheres, the chemical reaction between steam and methane takes place, resulting in the production of carbon monoxide and hydrogen gas. The reaction is represented by Eq. (3).

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (3)$$

To enhance process efficiency, it is common practice to subject carbon monoxide to the water–gas shift reaction, as denoted by Eq. (2), to increase the production of hydrogen. The hydrogen produced is often refined through the utilization of a pressure swing adsorption (PSA) technique to eliminate impurities such as carbon dioxide and other residual substances like carbon monoxide. The heat necessary for the process of reforming is typically supplied through the combustion of a fraction of the hydrocarbon feed that is being introduced, as well as by the combustion of waste gases that contain hydrogen (H_2) and carbon monoxide (CO) [33]. One of the primary drawbacks associated with this process is the considerable size and elevated cost of plant materials, which can be attributed to the specific pressure and temperature conditions required [34]. One further drawback of SMR is its detrimental effect on the environment, which is manifested through the significant release of carbon dioxide (CO_2) [35]. The process requires high temperatures, typically around 800–1000 °C, which are achieved by burning fossil fuels, leading to the emission of greenhouse gases and other pollutants. While CCS technologies can mitigate this, they are not always implemented due to cost and technological limitations[36].

SMR also consumes a large amount of natural gas, a non-renewable resource, which could exacerbate the depletion of natural gas reserves and lead to increased reliance on fossil-fuel extraction, with attendant environmental and social issues such as habitat destruction, water contamination, and land use conflicts[37]. Moreover, the SMR process has inherent energy inefficiency because a significant portion of the energy content of the natural gas feedstock is lost as heat rather than being converted into hydrogen. This inefficiency necessitates additional energy input, increasing operational costs and energy use [38]. The water–gas shift reaction, which is a subsequent step to SMR to increase hydrogen yield, produces carbon dioxide as a byproduct, adding to the environmental burden[37]. Furthermore, the centralized production model of SMR plants necessitates the transportation of hydrogen to end users, which can lead to further emissions and safety concerns associated with the handling and transfer of hydrogen [39].

The infrastructure for transporting and storing hydrogen is also less developed compared to that for natural gas, which adds to the complexity and cost of using hydrogen produced by SMR. In addition, the catalysts used in SMR are susceptible to deactivation by impurities in the natural gas, such as sulfur compounds, which necessitates pretreatment of the feedstock, adding to the cost and environmental footprint of the process [39]. The SMR process, while economically viable for large-scale hydrogen production, often locks in a technology that is carbon-intensive and may hinder the transition to renewable energy sources and cleaner technologies for hydrogen production, such as electrolysis using renewable electricity. Recent advancements focus on integrating CCS to reduce CO_2 emissions. Development in catalyst technologies aims to increase efficiency and reduce operational costs.

The process flow diagram in Fig. 2, illustrates a reforming reactor, water shift reactors (WGS), high-temperature (HT) and low-temperature (LT), syngas purification, CO_2 compression, transportation, sequestration, and hydrogen storage [40]. The reforming reactor facilitates the reaction between natural gas and steam under high pressure, resulting in the production of syngas, which is a combination of hydrogen and carbon monoxide. The reaction occurs in the presence of catalysts based on nickel, resulting in the production of carbon monoxide and syngas rich in hydrogen. Oni et al. [40] stated that the syngas undergoes cooling and is introduced into the WGS reactors, where the carbon monoxide is transformed into carbon dioxide and hydrogen by the introduction of steam. The HT and LT water gas shift reactors are connected sequentially, with catalysts being used in each reactor, respectively. The hydrogen generated undergoes purification in the syngas purification unit, also known as the amine unit. Subsequently, the substance is subjected to increased pressure and subsequently stored within

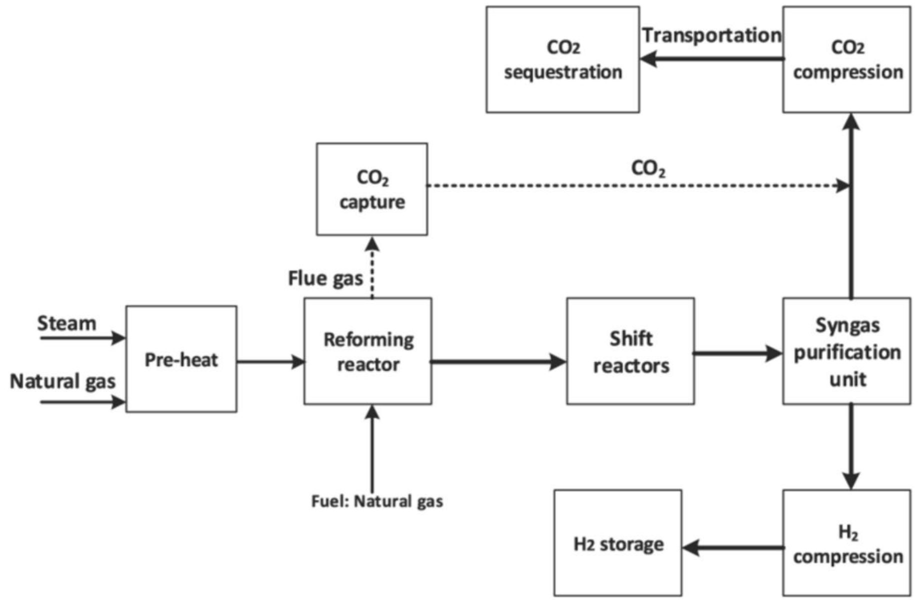

Fig. 2 Simplified process flow diagram of steam methane reforming with carbon capture and storage (SMR-CCS) Reproduced with permission from Oni et al. [40]. Copyright 2023, Elsevier

the designated storage tanks. The CO_2 emissions generated by the syngas purification unit are pressurized and conveyed via a pipeline to an underground cavern. In the absence of CCS, the syngas produced by the WGS reactors is cooled and then directly sent to the syngas purification/ PSA unit. C_{O2} emissions are directly released into the atmosphere.

The infrastructural inertia and existing investments in SMR can also create a barrier to adopting these cleaner technologies. Consequently, while SMR plays a critical role in the current hydrogen economy, its environmental and economic drawbacks, along with its impact on natural resource depletion and contribution to climate change, mark it as a technology with significant disadvantages that must be addressed in the transition to a sustainable energy future. The advantages and disadvantages are shown in Table 1.

Biological

An alternative method for generating hydrogen from biomass involves the application of biologic technology, namely the anaerobic digestion process that cultivates bacteria through fermentation in bioreactors under dark conditions, or the

Table 1 Advantages and disadvantages of SMR

Advantage	Disadvantage
Economically efficient	High CO_2 emissions
Established technology with a proven economic record for large-scale production	Generates significant amounts of CO_2, contributing to greenhouse-gas emissions
High hydrogen yield	Energy intensive
Produces a high yield of hydrogen from methane, with a relatively high efficiency compared to other fossil-fuel-based methods	Requires a lot of energy to achieve the high temperatures needed for the reaction, which often comes from burning fossil fuels
Mature technology	Dependence on natural gas
Well-understood, with extensive operational experience and industrial application	Relies on natural gas, a non-renewable resource, which can lead to resource depletion and energy security issues
Scalability	Infrastructure needs
Can be scaled to meet large industrial demands for hydrogen production	Requires significant infrastructure for gas distribution and handling, which is costly to build and maintain
Integration with CCS	CO_2 capture required
Can be integrated with carbon capture and storage (CCS) to reduce emissions, though this is not always cost-effective or feasible	Effective CCS is necessary to make the process less harmful to the environment, adding complexity and cost
Feedstock flexibility	Catalyst degradation
Capable of using a variety of hydrocarbon feedstocks, not just methane	Catalysts used can be sensitive to impurities, leading to degradation and the need for replacement or regeneration

photo fermentative process that utilizes algae and bacteria in photobioreactors under light conditions [41]. Biologic methods are regarded as potential approaches for the production of hydrogen, characterized by low pollution levels and great efficiency [42]. The dark fermentation process is conducted by anaerobic bacteria which transform carbohydrate-rich substances into hydrogen, carbon dioxide, and other acidic byproducts [43]. This reaction can be represented as below:

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2 \quad (4)$$

Fermentation offers various advantages, including its straightforward reactor design and operation, the ready availability of fermentative bacteria, the ability to utilize diverse waste sources, and the potential for achieving high rates of hydrogen production in comparison to alternative biologic processes. One of the primary obstacles encountered in dark fermentation is the comparatively limited output capacity per unit of capital expenditure [44]. To address this issue, significant research endeavors have been undertaken to advance the development of two-stage systems to extract supplementary energy. This is because the volatile fatty acids possess the potential to be readily converted into methane through the utilization of proven anaerobic digestion technology [45].

Figure 3 [24] illustrates the schematic representation of the two-stage method. An additional benefit of employing a two-stage integration approach is the ability to adjust each phase of the process independently, hence enhancing the efficiency of fermentation. Biologic hydrogen production, involving biotechnological methods like biophotolysis, photo-fermentation, and dark fermentation, utilizes microorganisms such as algae, bacteria, and archaea to produce hydrogen from various organic substrates. Despite its sustainable potential, the biologic process of hydrogen production faces several limitations as shown in Table 2. First, the rate of hydrogen production is generally low compared to chemical methods like SMR, which limits its commercial scalability. The metabolic pathways in microorganisms that lead to hydrogen production are inherently less efficient, and the energy conversion efficiency from sunlight to hydrogen in photosynthetic organisms is low [46]. This inefficiency stems from the fact that only specific wavelengths of light can be utilized, and the conversion processes do not fully exploit the energy content of the light.

The purity of the hydrogen produced biologically is often lower, requiring additional steps for purification before it can be used in fuel cells or for other industrial purposes which adds complexity and cost to the process. Moreover, biologic systems require precise control of environmental conditions, such as temperature, pH, and nutrient concentration, which can be difficult to maintain on a large scale and may lead to inconsistent production rates [47]. There is also competition for substrate resources since some of the organic materials suitable for hydrogen production are also valuable for food or other bio-based industries. In addition to operational challenges, biologic hydrogen production systems are sensitive to contamination by other microorganisms that can outcompete the hydrogen-producing species or disrupt the process [48]. Sustaining a pure culture over the long term is challenging and increases operational costs. The long-term stability and robustness of the biologic systems are

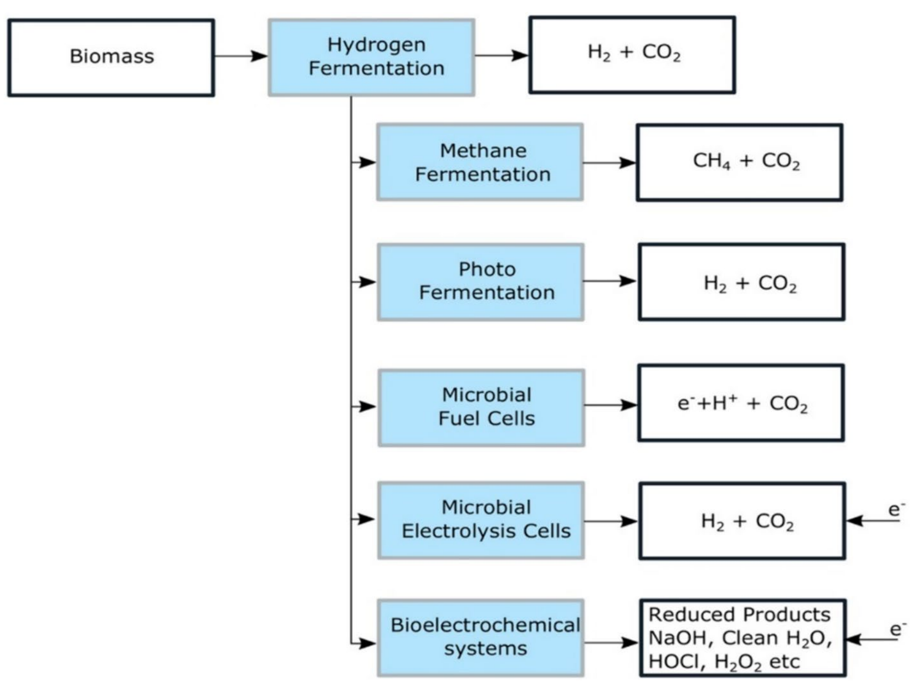

Fig. 3 Overview of biohydrogen production process. Reproduced with permission from Zhang et al. [24]. Copyright 2023, Elsevier

Table 2 Advantage and disadvantage of biologic process

Advantages	Disadvantages
Renewable and low-impact resource	Low production rates compared to chemical processes
Environmentally friendly	Needs significant purification to reach high purity
Can utilize organic waste streams	Requires stable and controlled conditions
Produces minimal greenhouse gasses	Prone to biologic contamination
Uses abundant substrates like water	High initial setup and operational costs
Carbon–neutral potential	Competition with food production for substrates
Technological advances may improve efficiency	Sensitive to environmental changes, affecting yield
	Limited by current infrastructure and scalability challenges
	Research and development can be time-consuming and expensive

also concerns, as the production organisms may mutate or lose their production capabilities over time, necessitating continuous monitoring and potentially frequent reinoculation of the system.

The initial setup and maintenance costs for biologic systems are significant when considering the need for large bioreactors and controlled environmental conditions. The land footprint for such systems can also be substantial, which may be a competing interest with agriculture or conservation efforts [48]. Moreover, the lifecycle environmental impact of these systems, while potentially lower than fossil fuel-based methods, still requires assessment to ensure that the inputs and outputs do not cause unintended ecological harm. Furthermore, the integration of biologic hydrogen production into the current energy infrastructure poses challenges. The hydrogen distribution network is predominantly designed for hydrogen generated from fossil fuels, and the lower production volumes from biologic methods may not justify the investment in new distribution systems or the modification of existing ones [49].

Lastly, research and development in this field are expensive and time-consuming, with uncertainty about the timeframe for overcoming the technical barriers to make biologic hydrogen production a viable alternative on a global scale. Current research [50–52] focuses on genetically engineering microorganisms to enhance hydrogen yield and process efficiency. Hybrid systems combining dark and photo-fermentation are being explored to optimize hydrogen production. In conclusion, while biologic hydrogen production holds promise for a sustainable and green future, its limitations related to efficiency, scalability, cost, and integration into existing systems pose significant hurdles that require innovative solutions and continued research before it can become a mainstream technology.

Water Electrolysis

The process of water decomposition can be achieved by applying direct electric current, resulting in the production of hydrogen and oxygen through redox reactions. An electrolyzer is a device that facilitates the simultaneous occurrence of oxidation and reduction reactions, resulting in the production of hydrogen and oxygen gasses [24]. In theory, it is possible to connect many electric power generating sources, such as Photovoltaic, wind and other renewable energy sources, nuclear, fossil fuel, or biomass electric-power plants, to an electrolyzer to generate hydrogen and oxygen. The overall reaction is as below:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \quad (5)$$

There are three potential methods for conducting electrolysis to separate the H_2O molecule, depending on the temperature requirements [31]. First method is the process of electrolysis, specifically cold electrolysis, refers to the decomposition of liquid water at or near the surrounding temperature as shown in Fig. 4 [53]. Alkaline and proton exchange membrane (PEM) electrolysis cells are viable options for utilization.

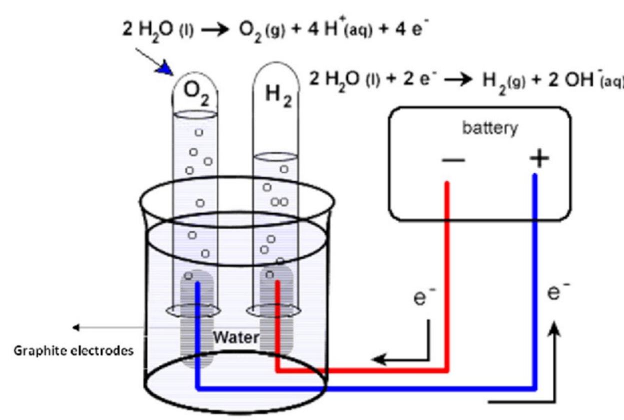

Fig. 4 Electrolysis process. Reproduced with permission from Yuvaraj and Santhanaraj [53]-Open Access. Copyright 2023, Scientific Electronic Library Online

Alkaline electrolysis is one of the oldest and most established electrolysis technologies, having been used for over a century [54]. It operates using a liquid alkaline electrolyte, such as potassium hydroxide (KOH) or sodium hydroxide (NaOH) [55]. The key features of alkaline electrolysis include its relatively high efficiency, which typically ranges between 60 and 75%, and its lower capital costs compared to other electrolysis technologies due to its maturity and widespread adoption [56]. Alkaline electrolyzers are known for their long operational life and durability. They typically operate at temperatures between 60 and 90 °C and atmospheric pressure [57], making them robust and reliable for industrial applications. However, alkaline electrolysis systems tend to be bulkier and have slower dynamic response times compared to more modern technologies.

Polymer Electrolyte Membrane (PEM) electrolysis represents a more recent and advanced electrolysis technology. It utilizes a solid PEM to conduct protons from the anode to the cathode, while electrons travel through an external circuit [58]. PEM electrolysis is characterized by its high efficiency, and its ability to operate at high current densities [59]. One of the significant advantages of PEM electrolysis is its compact design and rapid response to changes in power supply, which makes it highly suitable for integration with renewable energy sources like wind and solar power [60]. PEM electrolyzers typically operate at lower temperatures (around 50–80 °C) and can achieve higher pressures than alkaline electrolyzers, reducing the need for subsequent compression of the produced hydrogen [61]. However, the higher cost of the membrane and catalyst materials, such as platinum, presents a challenge for widespread adoption.

The second method is high-pressure electrolysis. High-pressure electrolysis is considered to be an appealing option due to its ability to facilitate the compression and storage of hydrogen and oxygen [24]. To enhance the process efficiency, it is necessary to elevate both temperature and pressure. In addition, the water is supplied in a state of pressurized liquid. Pressurizing water is thermodynamically more efficient compared to compressing hydrogen and oxygen products. Nevertheless, it is important to consider a design trade-off in relation to the operating pressure, as excessively high pressures might result in diminished efficiency and increased expenses. Last method is solid oxide electrolysis cells using high temperature steam as the electrolyte [24]. In this particular scenario, the transformation of water into steam occurs through the utilization of thermal energy. Furthermore, the electrochemical bath can be heated either directly, using steam, or indirectly, using heat transfer.

Solid oxide electrolysis is a high-temperature electrolysis technology that uses a solid oxide or ceramic electrolyte to conduct oxygen ions from the cathode to the anode [62]. This technology operates at temperatures ranging from 600 to 850 °C, significantly higher than those of alkaline and PEM electrolyzers [63]. The high-operating temperatures allow solid oxide electrolyzers to achieve very high efficiencies, often exceeding 80%, as the heat can be used to reduce the electrical energy required for the electrolysis process [63]. Solid oxide electrolysis is particularly advantageous when integrated with processes that produce high-temperature waste heat, such as industrial manufacturing or concentrated solar-power systems. However, the high-operating temperatures also pose challenges in terms of material durability and system complexity, leading to higher capital and maintenance costs.

Each of these water electrolysis technologies offers unique advantages that make them suitable for different applications. Alkaline electrolysis, with its established technology and lower costs, is ideal for large-scale industrial hydrogen production. PEM electrolysis, with its compact design and rapid response capabilities, is well-suited for renewable energy integration and decentralized hydrogen production. Solid oxide electrolysis, with its high efficiency and potential for integration with high-temperature processes, offers significant advantages in specialized industrial applications.

Electrolyzers can be scaled to match the production requirements of various applications, from small-scale industrial processes to large-scale hydrogen production facilities. This flexibility also extends to the integration with renewable energy sources; electrolyzers can be powered using surplus electricity from wind, solar, or hydroelectric sources, making the hydrogen produced "green" and renewable. When powered by renewables, electrolysis does not produce direct greenhouse-gas emissions, which makes it an essential technology for decarbonizing sectors that are difficult to electrify directly, such as heavy industry and transportation [64]. Water electrolysis is also beneficial because it can provide grid-balancing services. Since electrolyzers can be turned on and off quickly, they can absorb excess electrical grid capacity when supply exceeds demand, helping to stabilize the grid and allowing for the integration of more intermittent renewable energy sources.

However, the process is not without its limitations. The efficiency of water electrolysis is often cited as a disadvantage. The energy conversion efficiency—from electrical energy to the chemical energy of hydrogen—is currently between 60 and 80%, depending on the specific technology used (alkaline, PEM, or solid oxide electrolyzers) [65]. This means that a significant portion of the electrical energy used is not converted into chemical energy and is instead lost as heat. Economic considerations are another limitation. The capital costs of electrolyzers are high, and the operational costs can be significant, primarily due to the energy required. The cost of electricity is the most substantial factor in the overall cost of producing hydrogen by electrolysis, making the process less competitive in regions where electricity prices are high or where low-carbon electricity is not available [66]. Moreover, while electrolysis is a mature technology, there is still room for improvement in terms of durability and performance. Electrolyzer systems require maintenance and replacement over time, especially the electrodes, which can degrade with use. Advances in materials science could lead to more robust and efficient electrolyzer designs, further reducing operational costs and increasing the technology's attractiveness [67]. In conclusion, water electrolysis for hydrogen production has distinct advantages, particularly concerning environmental sustainability and the production of high-purity hydrogen.

Its flexibility, in terms of scale and integration with renewable energy, makes it a key technology in the transition to a low-carbon economy. Kumar and Lim [68] stated that advancements in electrolyzer technology, including PEM and Solid Oxide Electrolysis Cells (SOEC), have improved efficiency and reduced costs. Integrating renewable energy sources with electrolysis is a key area of development to produce green hydrogen. Nonetheless, efficiency and economic limitations remain barriers to its widespread adoption. Continued research and development could lead to advancements that overcome these challenges, making electrolysis a cornerstone of future hydrogen economies. The balance between these factors will shape the role of electrolysis in global hydrogen production strategies.

Gasification

Gasification is a well-established method utilized for the production of syngas by converting solid fuels. This process enables the extraction of pure hydrogen from the resultant syngas. Gasification and partial oxidation are tightly interconnected processes. required to convert the fuel into a gaseous state. In the temperature range of 300 to 2000 °C, the fuel undergoes a reaction with a gasification agent, such as air, oxygen, steam, or a combination thereof [24]. The objective is to generate synthesis gas. The synthesis gas comprises hydrogen. The substance that can be divided into its constituent parts, and carbon monoxide that can undergo a chemical transformation to become carbon dioxide. The liberation of additional hydrogen can be achieved by the process of water–gas shift [33].

The gasification process can be classified as either autothermal or all-thermal, depending on the method used to supply heat [24]. Auto-thermal reforming/gasification is a process that integrates the partial oxidation and steam reforming techniques as shown in Fig. 5 [69]. The technique described employs the usage of partial oxidation for heat generation and steam reforming to enhance the production of hydrogen, hence achieving a thermally neutral outcome [70]. The reaction can be described as follows:

$$CH_4 + H_2O + \frac{1}{2}O_2 \rightarrow 3H_2 + CO_2 \tag{6}$$

Gasification is a process that converts organic or fossil-based carbonaceous materials into carbon monoxide, hydrogen, and carbon dioxide, primarily using a controlled amount of oxygen and/or steam. The central advantage of gasification is its ability to turn a variety of feedstocks, especially low-value resources such as coal, petcoke, biomass, and municipal solid waste, into valuable syngas (synthetic gas), from which hydrogen can be extracted [71]. This versatility makes it an attractive option for exploiting locally available resources and can reduce dependence on external energy supplies. Moreover, gasification can process materials that are not suitable for use in other energy recovery processes, potentially reducing waste and exploiting energy from biomass that would otherwise not be used.

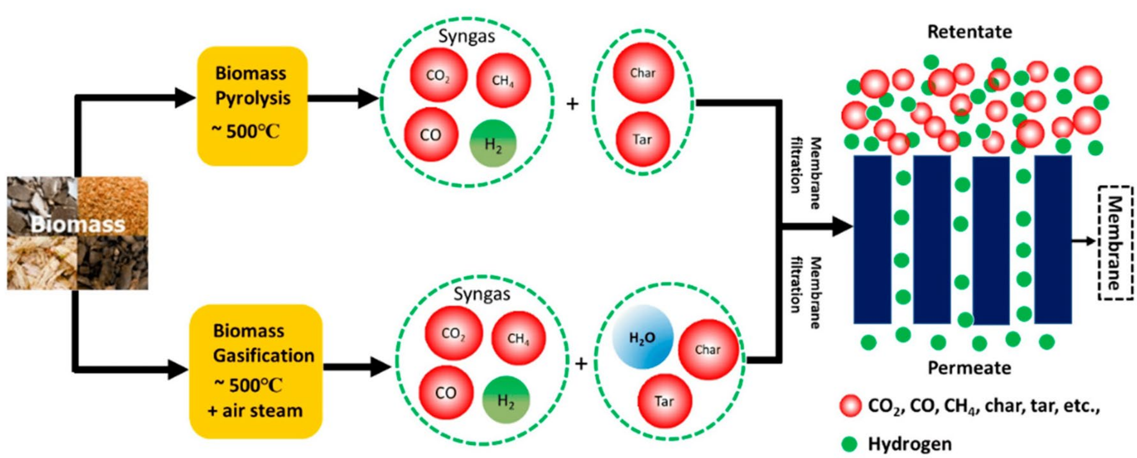

Fig. 5 Gasification process. Reproduced with permission from Besha et al. [69]. published under an open access Creative Common CC BY license. Copyright 2023, MDPI

Another significant benefit of gasification is that it enables the large-scale production of hydrogen [72]. Given the extensive infrastructure and technology developed for coal and biomass processing, gasification can contribute to meeting the high demand for hydrogen, particularly in industrial applications such as refining, ammonia production, and as a reducing agent in steel manufacturing. When coupled with CCS technologies, gasification can be part of a clean energy solution, mitigating the carbon footprint traditionally associated with coal and other carbon-based feedstocks. The process efficiency of gasification is also a notable advantage; it has the potential to produce more hydrogen per unit of feedstock than traditional combustion processes [73]. This is because gasification operates at high temperatures, which, combined with the subsequent water–gas shift reaction, can convert a significant portion of the carbon content in the feedstock into hydrogen. However, the process of gasification has several limitations and challenges [74]. Economically, the initial capital investment for a gasification plant is high, which can be a barrier to entry for new market participants. The complexity of the technology requires significant expertise and control, which can increase the costs of training and operation. Moreover, the operation of a gasification plant involves substantial maintenance expenses due to the harsh operating conditions that can lead to equipment wear and tear.

From an environmental perspective, gasification can produce a considerable amount of carbon dioxide, making it less favorable in terms of greenhouse0gas emissions compared to lower-carbon hydrogen production methods. Although the integration of CCS can mitigate this issue, the viability and economics of CCS technology are still under scrutiny, with operational CCS projects being limited in number and scale [75]. The water consumption of gasification is also a drawback, as significant amounts of water are required for the steam that facilitates the gasification process.

Innovations in gasifier designs and the use of advanced materials are improving the efficiency of hydrogen production [76]. The integration of CCS with gasification processes aims to mitigate environmental impacts. However, in areas where water is scarce, this can be a critical concern and limit the applicability of the technology. Technological limitations also include the challenge of tar production during gasification, which can lead to operational difficulties and additional processing steps to clean the syngas [74]. The variability in feedstock composition can also lead to inconsistencies in syngas composition, affecting the efficiency and stability of the hydrogen production process.

In summary, while gasification offers a route to transform a wide range of feedstocks into hydrogen, its economic, environmental, and technological limitations must be carefully managed. Advances in gasifier designs, improved catalysts for syngas cleanup, and better integration with CCS could help to address these challenges, making gasification a more competitive and sustainable option for hydrogen production. The future of gasification will depend on balancing these advantages with the need to minimize its environmental impact and enhance its economic feasibility.

Fusion

Using fusion to produce hydrogen represents a cutting-edge intersection of nuclear physics and sustainable energy research, offering a potentially limitless and clean energy source. Fusion, the process that powers the sun, involves combining light atomic nuclei to form heavier ones, releasing enormous energy in the process. Hydrogen, particularly its isotopes deuterium and tritium, plays a critical role in fusion reactors, serving as fuel for the fusion process. The most researched fusion reaction for energy production is the D–T (deuterium–tritium) reaction, where the fusion of these two hydrogen isotopes results in the production of helium and a neutron, releasing energy that can be converted into electricity [77]. The benefits of using fusion for hydrogen production are numerous. Fusion fuel is derived from water and lithium, with the former being abundant and the latter widely available, thus ensuring a vast supply for energy generation [78].

Unlike fossil fuels, fusion does not produce greenhouse gasses or long-lived radioactive waste, which aligns with global efforts to mitigate climate change [79]. Furthermore, fusion energy is inherently safe, with no possibility of a meltdown scenario akin to fission reactors, as the reaction cannot sustain itself without precise conditions [80]. However, the technology is still not commercially viable due to several challenges. Containing the hot plasma in which fusion occurs requires advanced magnetic confinement techniques, such as those used in tokamaks or stellarators, which are still under development. The International Thermonuclear Experimental Reactor (ITER) is a leading project in this area, aiming to demonstrate a ten-fold return on energy (10 times the energy put into the plasma [81].

The main limitation in utilizing fusion for hydrogen production lies in the engineering challenge of achieving and maintaining the extreme conditions necessary for fusion. Plasma temperatures must exceed 100 million degrees Celsius, which is significantly hotter than the core of the sun, requiring robust and sophisticated materials that can withstand such conditions [81]. Material degradation, neutron activation, and the handling of tritium—a radioactive substance—are significant technical hurdles that must be overcome [82].

Fusion research has been ongoing for decades, but it has accelerated in recent years with advances in superconducting magnets, laser technology, and computational modeling [83]. The potential of fusion to provide a steady, continuous supply of energy contrasts with the intermittency of renewable sources like wind and solar, making it an attractive complement to a diversified sustainable energy portfolio [84]. As of now, fusion remains in the experimental phase, with several research facilities around the world working on different methods to achieve a net-positive energy balance. Once this is accomplished, fusion could revolutionize hydrogen production by providing an energy-dense, environmentally benign, and virtually inexhaustible source of power for hydrogen generation through electrolysis or thermochemical water splitting. Table 3 shows the advantage and disadvantage of fusion energy in production of hydrogen.

Solar Water Splitting

Hydrogen production via solar water splitting is an emerging and promising method that harnesses solar energy to split water molecules into hydrogen and oxygen [85]. This process can be broadly categorized into photoelectrochemical (PEC) water splitting and photocatalytic water splitting [85, 86]. Photoelectrochemical water splitting utilizes semiconductor materials to capture sunlight and facilitate the electrochemical processes required for the separation of water into hydrogen and oxygen [87]. In a standard PEC cell, a semiconductor photoelectrode captures photons from sunlight, generating electron–hole pairs. The electrons and holes generated by the photochemical process are involved in the reduction and oxidation reactions occurring at the electrodes. This results in the production of hydrogen at the cathode and oxygen at the anode.

The effectiveness of PEC water splitting relies heavily on the characteristics of the semiconductor materials employed, such as their bandgap, stability, and surface properties. Titanium dioxide (TiO_2), tungsten trioxide (WO_3), and hematite (Fe_2O_3) have undergone thorough examination for their potential application in PEC cells because of their appropriate bandgaps and resistance to solar irradiation [88]. Furthermore, the progress made in nanostructuring and doping of these materials has demonstrated the potential to improve their efficiency and stability.

Photocatalytic water splitting is the process of dispersing photocatalyst particles in water, which then absorb sunlight and catalyze the separation of water molecules into hydrogen and oxygen [89]. Like PEC water splitting, this process depends on the creation of electron–hole pairs when the photocatalyst absorbs light. Electrons catalyze the reduction of water to generate hydrogen, while the holes catalyze the oxidation of water to generate oxygen.

TiO_2 are commonly studied photocatalysts due to their extensive research on their photocatalytic capabilities [90]. Modifying photocatalysts with co-catalysts, such as platinum or nickel, can enhance the efficiency of photocatalytic

Table 3 Advantage and disadvantages of fusion energy in the production of hydrogen

Advantages	Disadvantages
Virtually unlimited fuel supply	Technological challenges
Uses deuterium and tritium, which can be extracted from seawater and lithium, provide a nearly unlimited fuel supply	The technology to achieve and maintain the conditions for fusion is complex and not yet fully developed
High energy output	High initial investment
Fusion reactions release significantly more energy per unit of fuel than fossil fuels or fission nuclear reactions	Building a fusion reactor requires a large initial capital investment, and the technology is still not cost-competitive
Environmentally friendly	Material and engineering issues
Produces no greenhouse0gas emissions and only low levels of short-lived radioactive waste	Developing materials that can withstand the extreme conditions inside a fusion reactor is still a research challenge
Safety	Radioactive tritium handling
Fusion reactions do not have the risk of a meltdown and can be quickly stopped by disrupting the plasma	Safe handling and containment of tritium, a radioactive material, are necessary, which involves complex safety measures
Supports decarbonization	Plasma confinement
Can contribute to large-scale hydrogen production for fuel and energy without carbon emissions	Magnetic confinement systems like tokamaks and stellarators are expensive and technically demanding
Complementary to renewable energy	Research and development pace
Fusion energy can provide a consistent power output that complements the intermittency of renewable sources	Progress in making fusion a practical energy source has been slower than anticipated, with many scientific hurdles still to overcome
Reduced long-term radioactive waste	Energy Input vs. Output
Compared to conventional nuclear fission, fusion produces less long-term radioactive waste	Current fusion experiments consume more energy than they produce, though this is expected to change with future advancements
Global collaboration and innovation	Limited operational experience
Fusion research is supported by international collaborations, pooling global scientific expertise and resources	There is limited experience with the long-term operation of fusion reactors, as no commercial-scale reactor is in operation yet

water splitting. These co-catalysts aid in the separation of electron–hole pairs and improve the overall reaction kinetics. Moreover, the advancement of innovative photocatalyst materials, such as metal–organic frameworks (MOFs) and graphitic carbon nitride, has demonstrated substantial promise in attaining elevated rates of hydrogen production when exposed to solar radiation [91].

Figure 6a depicts the basic mechanisms involved in a photoelectrochemical device, specifically a two-electrode system with a solitary absorber photoanode [92]. The technology of solar photoelectrochemical (PEC) hydrogen production holds great promise in terms of its potential to offer environmentally friendly, economically efficient, and secure operation. Essentially, when a PEC semiconductor device possessing the precise characteristics is submerged in a liquid electrolyte and exposed to external sunlight, the energy carried by photons is transformed into electrochemical energy, enabling the direct separation of water into hydrogen and oxygen (chemical energy) [92]. Consequently, the sporadic solar energy is transformed into a more naturally storable form of energy through chemical bonding. The photocatalytic water splitting reaction is an endergonic reaction as shown in Fig. 6b [92]. The energy necessary to initiate photocatalytic and PEC water splitting is supplied by light, preferably sunlight.

Economy Prospect Between Fusion, Gasification, Steam Methane Reforming, Biologic, and Electrolysis

The economic feasibility of hydrogen production technologies is essential for their adoption and advancement. Various hydrogen production methods, including SMR, Electrolysis, Gasification, Biologic Processes, and Fusion, highlight their advantages and disadvantages, offering valuable insights for those interested.

Currently, SMR is the most economically efficient technique for producing hydrogen [93]. This established technology leverages the existing infrastructure, lowering initial capital expenses. In addition, SMR exhibits a substantial hydrogen output, rendering it highly effective for extensive industrial use. Nevertheless, the approach has notable disadvantages, mainly due to its substantial carbon emissions. SMR, when not used in conjunction with CCS, produces a significant amount of CO_2, contributing to the overall expenses. Moreover, the reliance of SMR on natural gas, which is a finite resource, can result in supply limitations and price fluctuations, thereby impacting its long-term viability [93].

Electrolysis, however, provides significant environmental advantages, particularly when fuelled by renewable energy sources [94]. This technique generates green hydrogen without any emissions, significantly contributing to a sustainable energy future. Electrolysis is a versatile and scalable process that efficiently utilizes excess electricity generated from renewable sources. However, electrolysis encounters economic obstacles due to its high operational expenses, predominantly influenced by the cost of electricity. Electrolysis's current energy conversion efficiency ranges from 60 to 80%, resulting in substantial energy losses and further affecting its economic viability [9]. Electrolysis is responsible for 4% of the global energy demand, making it the leading hydrogen production technology. The estimated production cost for electrolysis is $10.3 per kilogram [64].

Gasification is a flexible method that can convert different types of raw materials, such as coal, biomass, and municipal solid waste, into hydrogen [12]. This adaptability enables the utilization of resources that are readily accessible in a particular area, which makes it a desirable choice for regions that have ample supplies of raw materials. Gasification is especially well-suited for hydrogen production on a large scale, which is crucial for industrial purposes. Nevertheless, the technology necessitates a substantial initial financial outlay owing to its intricacy and the requirement for preparatory

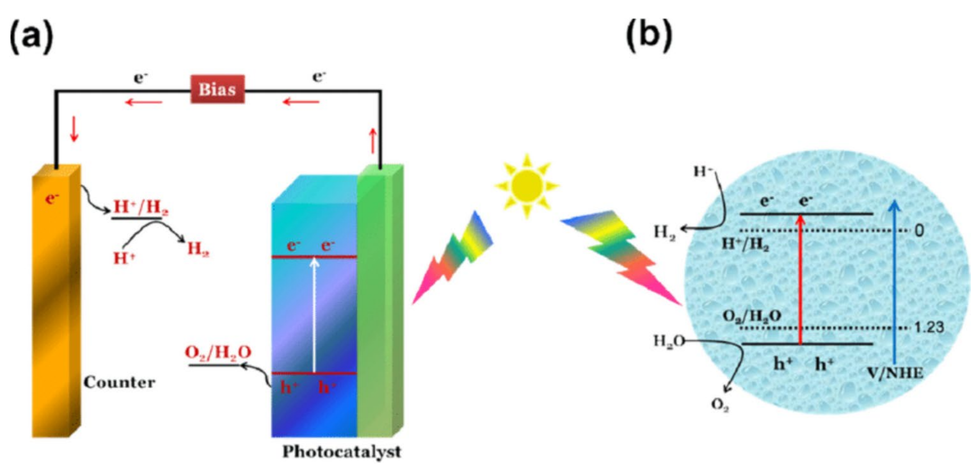

Fig. 6 The mechanism Principle of **a** Photoelectrochemical cell and **b** Photocatalytic water splitting process Reproduced with permission from Chandrasekaran et al. [92]. Copyright 2023, Korean Electrochemical Society

and purification procedures for the feedstock. In addition, gasification can result in significant carbon dioxide emissions, which require the implementation of CCS to reduce the environmental consequences. This, in turn, increases both the cost and complexity of the gasification process [12]. Thermochemical pyrolysis and gasification are economically feasible methods that have the greatest potential to become competitive on a large scale shortly. However, conventional methods still play a dominant role in H_2 production, with costs ranging from 1.34 to 2.27 dollars per kilogram [95].

Biologic processes used for hydrogen production utilize renewable organic waste, ensuring environmental friendliness and sustainability [96]. These methods have a significantly lower greenhouse0gas emission rate than technologies that rely on fossil fuels, providing an environmentally friendly alternative. Nevertheless, biologic processes encounter notable constraints, such as limited hydrogen production rates and elevated operational expenses [97]. Ensuring the required controlled conditions for biologic processes can be costly, and the systems are susceptible to contamination, which adds to the challenges of scaling up and making them economically viable.

Fusion embodies an advanced and potentially groundbreaking method for generating hydrogen [98]. Fusion technology offers the potential to generate significant amounts of energy while minimizing its impact on the environment. This is achieved by utilizing readily available fuels such as deuterium and tritium. If fusion is successfully achieved, it has the potential to offer an abundant and environmentally friendly source of energy for the production of hydrogen. However, fusion technology is currently in the experimental phase and is encountering substantial technological obstacles [99]. Constructing and upkeeping fusion reactors entail significant capital expenses, rendering it a prolonged commitment with uncertain financial gains. Attaining and sustaining the requisite circumstances for fusion is an intricate process requiring sophisticated materials and engineering remedies.

The economic viability of solar water splitting faces several challenges. The initial capital investment required for setting up solar water-splitting facilities is substantial [100, 101]. High costs associated with photovoltaic (PV) panels, electrolyzers, and other infrastructure components can be a barrier to widespread adoption [102, 103]. However, ongoing advancements in technology and economies of scale are expected to drive down these costs over time, making solar water splitting more economically competitive. The levelized cost of H_2 for PEC and polymer PEM electrolysis is almost similar about 9 $/kg$H_2$ [94].

To summarize, every hydrogen production technology possesses unique economic advantages and disadvantages. Table 4 summarizes the advantages and disadvantages of economic purposes. Currently, SMR is the most

Table 4 Summarization of advantage and disadvantages of economic purposes

Production method	Advantages	Disadvantages
Steam methane reforming	Cost-effective and well-established technology with existing infrastructure. High hydrogen yield	High carbon emissions unless combined with CCS, in addition to cost. Dependence on non-renewable natural gas
Electrolysis	Environmental benefits when powered by renewable energy. Flexible and scalable, can utilize surplus renewable electricity	High operational costs due to electricity expenses. Lower energy conversion efficiency (60–80%)
Gasification	Versatile: can use various feedstocks (coal, biomass, waste). Suitable for large-scale production, particularly in coal-rich regions	High initial capital investment. Significant CO_2 emissions are mitigated by CCS, which increases cost and complexity
Biologic process	Sustainable: uses renewable organic waste. Low pollution levels	Low hydrogen production rates. High operational costs and susceptibility to contamination
Fusion	Potential for high energy output with minimal environmental impact. Abundant and widely available fuel supply (deuterium and tritium)	Technological challenges: still in the experimental stage. High initial investment and uncertain economic returns
Solar water splitting	Solar water splitting harnesses the abundant energy of the sun to split water molecules into hydrogen and oxygen	High costs associated with photovoltaic (PV) panels, electrolyzers, and other infrastructure components

economically efficient method, but it has negative environmental impacts unless combined with CCS. When combined with renewable energy, electrolysis provides a sustainable solution. However, it faces challenges due to its high operational costs and efficiency issues. Gasification is a highly adaptable process that is well-suited for large-scale production. However, it necessitates substantial financial resources and the implementation of environmental measures to address its impact. Biologic processes exhibit environmentally friendly and sustainable characteristics, although they encounter difficulties regarding scalability and cost. Fusion exhibits significant promise, although it lacks economic feasibility due to technological obstacles and substantial upfront capital requirements. Comprehending these factors enables stakeholders to assess the economic viability of each technology, directing investments and policy choices toward the most advantageous and environmentally friendly hydrogen production methods.

Potential Solutions and Future Directions to Overcome the Existing Economic Challenges

To enhance the economic viability of hydrogen production technologies, it is imperative to investigate and adopt potential solutions that optimize efficiency, minimize expenses, and enhance sustainability. This paper presents various strategies and prospects for addressing the economic obstacles related to SMR, Electrolysis, Gasification, Biologic Processes, and Fusion.

SMR, although it is the most economically efficient technique for generating hydrogen, encounters substantial obstacles because of its carbon emissions [7]. An effective approach is to incorporate CCS technologies. By advancing the development of more economical and effective CCS systems, the carbon emissions associated with SMR can be substantially diminished, thereby enhancing its environmental sustainability [104]. In addition, using renewable natural gas (RNG) derived from biogas can reduce dependence on fossil fuels and minimize the overall environmental footprint [105].

Future developments for SMR involve the progression of catalyst technologies [93]. Investigating and innovating in cutting-edge catalysts can improve the effectiveness of the reforming procedure, resulting in lower operational expenses. Furthermore, implementing policy incentives that promote the manufacturing and utilization of low-carbon hydrogen can stimulate the acceptance of more environmentally friendly SMR technologies [22]. Government subsidies, tax credits, and other financial incentives are essential for ensuring the economic viability of CCS and RNG.

Electrolysis, when powered by renewable energy, provides substantial environmental advantages. However, it is frequently impeded by the expensive operational costs resulting from high electricity prices. To tackle this issue, integrating electrolysis systems with renewable energy sources, such as solar and wind, can offer inexpensive surplus electricity, thereby decreasing overall expenses [106]. Advancements in electrolyzer technology have the potential to enhance efficiency and lower expenses [107]. Advancements in membrane materials and electrode design can improve the performance and durability of electrolysis, resulting in reduced energy consumption and operational expenses [108].

An alternative approach to electrolysis is the advancement of decentralized hydrogen production systems [109]. By generating hydrogen near the location where it will be used, transportation and storage expenses can be reduced to a minimum. In addition, implementing more advanced energy storage systems to handle the fluctuating nature of renewable energy sources can contribute to a consistent and dependable electricity supply for electrolysis [110], thereby leading to further cost reductions.

Substantial upfront investments and environmental apprehensions hinder gasification's economic viability. To address these problems, enhancing gasification processes' efficiency and incorporating CCS technologies can be highly effective [111]. Plasma gasification and other advanced gasification techniques increase efficiency and reduce emissions, making them economically and environmentally feasible. In addition, using waste materials as feedstocks can lower feedstock expenses and help address waste management issues.

Regarding future directions, implementing policy frameworks that encourage the utilization of low-carbon hydrogen derived from gasification can yield advantages. Financial incentives, regulatory support, and research funding are influential factors that stimulate innovation and encourage the widespread use of cleaner gasification technologies. Establishing regional centers for hydrogen production utilizing readily accessible local resources can concurrently decrease transportation expenses and bolster regional economies.

While sustainable, biologic processes used for hydrogen production are hindered by low rates of production and expensive operational costs [112]. By utilizing genetic engineering and metabolic optimization of microorganisms, it is possible to improve the efficiency of these processes and consequently increase hydrogen production [112]. Creating strains that are more resistant to contamination and have increased resilience can also lower the expenses of maintaining controlled conditions.

Future research should prioritize integrating biologic hydrogen production with other renewable processes, specifically by combining anaerobic digestion with hydrogen fermentation [113]. Adopting this integrated approach makes it possible to improve overall efficiency and optimize the utilization of existing biomass resources. Furthermore, allocating funds from both the government and private sector toward pilot projects and scalable demonstrations can contribute to advancing biologic hydrogen production, making it more commercially feasible.

Despite its immense potential, Fusion is currently in the experimental stage and faces significant technological and financial challenges [114]. Sustained investment in research and development is essential for surmounting these challenges. International collaborations, such as the ITER project, are crucial for advancing fusion technology as they combine resources and expertise.

Prospects for fusion involve the advancement of materials capable of enduring extreme conditions and the enhancement of plasma confinement techniques [115]. Superconducting magnets and laser technology advancements can improve the effectiveness and practicality of fusion reactors. Creating unambiguous regulatory frameworks and making enduring financial commitments can offer the essential backing for advancing fusion technology to a state of commercial readiness.

Solar water splitting holds significant economic prospects as a sustainable and clean method for hydrogen production [85]. Its advantages, including abundant solar energy, environmental benefits, and energy independence, position it as a key technology in the transition to a hydrogen economy [85]. While economic challenges such as high initial costs and efficiency limitations exist, ongoing advancements and supportive policies are expected to drive down costs and enhance the viability of solar water splitting. As the world moves toward a sustainable energy future, solar water splitting has the potential to play a pivotal role in reducing carbon emissions, enhancing energy security, and fostering economic growth.

To sum up, addressing the economic obstacles of hydrogen production technologies necessitates a comprehensive strategy encompassing technological progress, policy assistance, and strategic investments. By identifying and targeting the specific limitations of each approach and capitalizing on their advantages, these proposed solutions and future strategies have the potential to establish a sustainable and financially feasible hydrogen economy. By conducting ongoing research, engaging in development efforts, and fostering collaboration, hydrogen has the potential to play a crucial role in attaining a more environmentally friendly and sustainable energy future.

Advantages of Hydrogen Production

Hydrogen storage exhibits a notably low self-discharge rate and a considerable energy density. Hence, it can be deemed a highly favorable selection for extended-term storage, a technically viable alternative for storage at the grid-scale level, and may be a potential solution for seasonal storage. Nevertheless, this does not apply to the systems that employ liquid-hydrogen storage and experience boil-off losses [26]. The eventual replacement of hydrocarbon-based fuels is anticipated due to the long-term benefits, adaptability, and clean energy associated with the alternative fuel source [116]. Moreover, hydrogen fuel is widely regarded as the most efficient and environmentally friendly energy carrier, as it only produces water as a byproduct upon combustion [117]. Hydrogen fuel is widely acknowledged as a self-contained and environmentally friendly energy source, possessing a considerably higher energy content in comparison to conventional fossil fuels [118]. Its global recognition is widespread.

Hydrogen has a high energy density for its weight, which makes it a good way to store and move energy for long periods [119]. The amount of energy in hydrogen per unit mass is very high. It has the highest energy density per unit of mass of any fuel that is widely used. This makes it a light and efficient way to carry energy. Hydrogen has a high energy density for its weight because its atomic weight is very low. This is good in situations where weight is important, like in aircraft or portable fuel cells. Hydrogen can quickly give off energy when it is burned or used in fuel cell processes [120]. This makes it useful when quick energy release is needed, like in some types of propulsion.

Hydrogen has the potential to function as a very effective medium for the transportation and storage of clean energy, hence enabling the use of surplus energy derived from renewable sources such as wind and solar power [121]. This particular aspect holds significant value in mitigating the intermittent nature of renewable energy generation. When hydrogen is employed in fuel cells for power generation or as a fuel source for cars, the sole resultant product is water vapor [122]. Hydrogen-based systems have the advantageous characteristic of generating no emissions during utilization, rendering them a compelling alternative for mitigating greenhouse0gas emissions [44]. The storage of hydrogen enables the disconnection of energy output and consumption. Hydrogen can serve as a means to store excessive energy during periods of surplus, therefore facilitating its utilization during instances of heightened energy demand or diminished renewable energy generation.

Hydrogen exhibits versatile applications throughout multiple sectors, encompassing transportation, industry, and power generation. Hydrogen exhibits versatile use as a fuel in various domains, including its application as a fuel source for fuel cell cars, its integration into industrial processes, and its utilization as an alternative power supply for contingency purposes, among other diverse applications [24, 123, 124]. Hydrogen can be held for prolonged durations without experiencing substantial energy dissipation. This characteristic renders it appropriate for extended-duration energy storage applications, such as energy storage throughout seasons for renewable energy sources. When hydrogen is generated by using renewable energy sources, such as solar or wind energy-powered electrolysis, it has a notably reduced carbon footprint compared to hydrogen derived from fossil fuels. Hydrogen fuel cell vehicles (FCVs) have the potential to enhance local air quality within the transportation sector due to their emission-free tailpipes, hence playing a significant role in mitigating air pollution levels in urban environments [125].

Hydrogen enables the implementation of seasonal energy storage, which plays a critical role in reducing the irregularity associated with renewable energy sources. Hydrogen can be kept for prolonged durations without experiencing substantial deterioration [126]. This characteristic makes it suitable for storing excess energy produced during high renewable energy output, such as in the summer when solar energy is abundant. Then, during seasons with lower energy output, such as winter, when there is less sunshine or wind, this stored energy can be used. Systems for storing energy in hydrogen can hold large amounts, making them suitable for storing energy at a utility-scale scale [127]. The concept of scalability holds significant importance in effectively managing the equilibrium between energy supply and demand over prolonged durations.

Hydrogen storage and conversion devices, such as fuel cells, have a notable advantage in terms of energy conversion efficiency, rendering them highly efficient for energy retrieval when required [128]. The storage of hydrogen enables the separation of energy production from energy utilization. This implies that surplus energy produced in one period can be stored and utilized in another, hence mitigating the necessity for auxiliary power sources or energy imports. The utilization of hydrogen for seasonal energy storage has the potential to enhance grid stability by mitigating variations in energy supply and demand. This measure can potentially reduce power outages and minimize the necessity for costly enhancements to the electrical grid infrastructure.

Challenges of Hydrogen Production

The utilization of hydrogen exhibits significant potential as a fundamental element in the establishment of a sustainable energy landscape. The technology possesses the capacity to minimize the unpredictable characteristics of renewable energy sources, such as wind and solar power, by the storage of surplus energy during periods of high availability and subsequent discharge during times of need [129–131]. Nevertheless, various obstacles must be overcome for hydrogen to become a practical and effective energy solution. These challenges encompass the effectiveness of hydrogen generation and utilization, the exorbitant expenses linked to hydrogen storage and transportation, and the establishing of essential infrastructure. Hydrogen storage and transportation using ammonia and the technology for liquefying hydrogen are important areas of focus.

Hydrogen exhibits a somewhat lower energy density in terms of volume, necessitating substantial amounts of hydrogen storage to accommodate a noteworthy quantity of energy [132]. The provision of specialized storage and transportation infrastructure demands significant financial investment. The construction and maintenance of hydrogen storage systems could lead to significant costs. The expenses of electrolyzers, compressors, fuel cells, and the necessary hydrogen delivery and storage infrastructure might pose significant barriers [133]. Hydrogen exhibits flammability characteristics and presents difficulties regarding safe storage and transportation. Implementing leak detection and mitigation measures plays a vital role in ensuring the secure utilization of hydrogen in energy storage systems.

Ammonia (NH_3) has recently garnered attention as a promising medium for hydrogen storage and transportation [134]. This interest is due to ammonia's high hydrogen content, which is 17.6% by weight, making it an efficient hydrogen carrier [135]. In addition, ammonia can be liquefied under relatively mild conditions (− 33 °C at atmospheric pressure) [136], which simplifies its storage and transport compared to hydrogen gas, which requires extremely low temperatures (− 253 °C) or high pressures [137]. The global infrastructure for ammonia production, storage, and transportation is well-established, primarily due to its extensive use in the agricultural sector as a fertilizer [138]. This existing infrastructure can be leveraged to support the hydrogen economy, potentially reducing the initial investment needed to develop new hydrogen-specific infrastructure.

One of the main advantages of using ammonia for hydrogen storage is its ability to be easily synthesized from nitrogen and hydrogen through the Haber–Bosch process, which is widely used and understood [139, 140]. Once synthesized, ammonia can be transported in liquid form using existing shipping and pipeline infrastructure. At the point of use, hydrogen can be released from ammonia through catalytic decomposition or by reacting it with water in a process known as ammonia cracking, yielding nitrogen and hydrogen [141]. These processes, while promising, still require optimization to improve their efficiency and reduce costs.

The phenomenon of hydrogen-induced embrittlement presents significant obstacles in the context of materials employed for hydrogen storage tanks and pipelines [142]. To mitigate the detrimental effects of hydrogen-induced embrittlement, specialized materials or coatings are required. Multiple techniques exist for the storage of hydrogen, encompassing gaseous, liquid, and solid-state storage methodologies [143, 144]. Each obstacle presents unique difficulties, such as the requirement for high-pressure containment or low-temperature storage when dealing with liquid hydrogen. Establishing the requisite infrastructure for hydrogen production, storage, and delivery is a substantial undertaking. This entails the establishment of a comprehensive infrastructure comprising hydrogen refueling stations or pipelines to facilitate the transportation of hydrogen to its intended recipients [145]. As the scale of hydrogen energy storage systems increases, potential issues may emerge regarding the preservation of efficiency, safety, and cost-effectiveness.

Liquefying hydrogen is another critical technology for efficient storage and transportation [143]. Liquid hydrogen has a much higher energy density compared to its gaseous form, making it more practical for applications requiring large amounts of hydrogen, such as in industrial processes and transportation [146]. However, the process of liquefying hydrogen is energy-intensive and costly. Hydrogen must be cooled to − 253 °C to be liquefied, which consumes a significant amount of energy—approximately 30–40% of the energy content of the hydrogen itself [147]. This high energy consumption is a major drawback that needs to be addressed to make liquid hydrogen a feasible option for large-scale storage and transport.

The development of more efficient cryogenic technologies and advanced insulation materials is crucial to reducing the energy requirements and costs associated with hydrogen liquefaction [146]. In addition, innovations in liquefaction processes, such as pre-cooling stages using liquid nitrogen or advanced compressors, are being explored to enhance efficiency [148]. These advancements could significantly lower the barriers to adopting liquid hydrogen as a mainstream solution for hydrogen storage and transport.

In conclusion, while hydrogen energy offers substantial benefits for a sustainable energy future, several challenges must be addressed to realize its full potential. The use of ammonia for hydrogen storage and transportation presents a viable alternative due to its high hydrogen content and existing infrastructure, but it requires further development to optimize the release of hydrogen. Similarly, advances in liquefaction technology are essential to make liquid hydrogen a cost-effective solution. Addressing these challenges through technological innovation and infrastructure development will be key to integrating hydrogen into the global energy system effectively.

Environmental of Hydrogen Production

The environmental impact of hydrogen production varies significantly depending on the method used. Currently, SMR is the predominant technique employed for the production of hydrogen [149]. Nevertheless, it has a high carbon footprint and presents notable environmental difficulties. The main environmental issue associated with SMR is the significant release of carbon dioxide that occurs during the process. SMR, unless paired with CCS technologies, makes a substantial contribution to greenhouse0gas emissions, thereby worsening the effects of climate change [149]. In addition, SMR is heavily dependent on natural gas, which is a finite resource. This reliance contributes to the depletion of resources and causes various environmental consequences associated with the extraction of natural gas, including habitat destruction, water contamination, and conflicts over land use [5].

Electrolysis is a more environmentally friendly approach to generating hydrogen, especially when fueled by renewable energy sources [94]. This procedure entails the division of water into hydrogen and oxygen through the application of an electric current. The origin of the electricity employed primarily determines the environmental footprint of hydrogen generated through electrolysis. Electrolysis can generate environmentally friendly hydrogen with a negligible ecological impact when fueled by renewable energy sources like wind, solar, or hydroelectric power [94]. In this situation, the process does not release any direct greenhouse gasses, which makes it an extremely sustainable choice. Nevertheless, if the electricity utilized for electrolysis is sourced from fossil fuels, the environmental advantages are considerably diminished as a result of the indirect emissions stemming from electricity production [150]. In addition, electrolysis necessitates a significant quantity of water, which can be problematic in areas experiencing water scarcity.

Gasification offers the potential to decrease waste and utilize resources of low value, but it also has significant environmental disadvantages [151]. The process releases substantial quantities of carbon dioxide, which makes it less desirable in terms of greenhouse gas emissions unless it is used in conjunction with CCS technologies. Furthermore, gasification demands a considerable upfront financial commitment and entails intricate technology that requires substantial expertise and maintenance [151]. The water usage in gasification is significant, presenting further environmental challenges.

Biologic hydrogen production techniques, such as dark fermentation and photo-fermentation, employ microorganisms to generate hydrogen from organic substrates [52]. These processes are regarded as environmentally sustainable because they make use of renewable organic waste and generate minimal amounts of greenhouse gasses. Nevertheless, the production rates of these methods are typically inferior when compared to chemical methods, thus restricting their potential for commercial expansion. In addition, biologic processes necessitate meticulous regulation of environmental conditions, which can pose difficulties in maintaining them on a large scale and may result in inconsistent rates of production [152]. The requirement for consistent and regulated conditions, coupled with the vulnerability to pollution, contributes to the difficulties and expenses of operation.

Solar water splitting methods have a minimal environmental impact as they do not rely on fossil fuels and produce hydrogen without generating greenhouse gasses [153]. The use of non-toxic and earth-abundant materials in photocatalysts and PEC cells can further enhance the sustainability of these technologies.

In conclusion, although hydrogen production shows potential for a sustainable energy future, it is imperative to carefully assess the environmental consequences associated with different production techniques [5]. Despite being the most cost-effective option at present, SMR has notable environmental disadvantages attributed to its high carbon dioxide emissions and reliance on natural gas. Electrolysis provides a more environmentally friendly option, particularly when fueled by renewable energy. However, the extent of its positive impact on the environment depends on the origin of the electricity used. Gasification is a highly adaptable process, but it has the drawback of being both carbon-intensive and requiring a significant amount of water. Biologic processes are capable of being maintained over time without depleting resources, but they encounter difficulties in terms of being able to be expanded and regulated. To achieve sustainable development of hydrogen production technologies, it is crucial to address the environmental impacts by utilizing technological advancements, implementing policy incentives, and integrating renewable energy sources.

Application of Hydrogen

Hydrogen energy storage in transportation pertains to using hydrogen as an energy carrier and storage medium across many transportation modalities, encompassing automobiles, locomotives, vessels, and even aircraft [24, 154, 155]. Hydrogen is often regarded as a prospective substitute for conventional fossil fuels because it can mitigate greenhouse-gas emissions and decrease reliance on petroleum resources [156]. FCVs represent a prevalent utilization of hydrogen energy within transportation [157]. Hydrogen is a fuel source to generates electrical energy via a chemical reaction within a fuel cell, subsequently driving an electric motor. FCVs are widely recognized for their ability to operate with zero emissions. In addition, FCVs boast extended driving ranges and rapid recharging capabilities [157].

Some types of cars employ hydrogen as a fuel source within their internal combustion engines, akin to the utilization of petrol or diesel fuel in conventional engines [158]. Although Hydrogen Internal Combustion Engine (H2ICE) cars are not as efficient as fuel cells, they are comparatively straightforward to produce and have been employed in specific applications [159]. Moreover, hydrogen fuel cells can potentially serve as a viable energy source for the propulsion of trains and buses. These cars benefit from emitting zero pollutants, rendering them well-suited for integration into public transit networks. The potential utilization of hydrogen in maritime and aviation sectors is now under investigation [154]The transportation industry is now engaged in research efforts to incorporate hydrogen into various sectors to mitigate carbon emissions.

The utilization of hydrogen energy storage has the potential to assume a significant part in the process of grid balancing, thereby offering a viable solution to the challenges posed by the intermittent and variable nature of renewable energy sources such as wind and solar power [160]. Hydrogen energy storage exhibits notable efficacy in grid balancing due to its capacity for swift dispatch upon demand. In contrast to several alternative energy storage methods, hydrogen exhibits the capacity to deliver sustained power output over prolonged durations, rendering it a viable option for addressing grid balancing requirements in both immediate and prolonged timeframes [161]. Hydrogen can efficiently store substantial quantities of energy, rendering it a viable option for grid stabilization over prolonged durations, including several days or even weeks. Hydrogen fuel cells provide the capability to rapidly increase their power output, so enabling them to efficiently contribute to the electrical grid in response to immediate requirements. This characteristic renders them very suitable for effectively managing abrupt variations in the availability or use of energy.

The utilization of hydrogen storage facilitates the disentanglement of energy production timing, wherein renewable sources provide energy from energy consumption timing, whereas consumers require it [124]. This process effectively diminishes wastage and enhances the stability of the grid. Hydrogen energy storage can store surplus renewable energy during periods of generation surpassing demand, afterward releasing it when there is a need within the system [161]. This finding provides evidence in favor of incorporating a larger proportion of renewable energy sources into the overall energy portfolio. With the continuous advancement of technology and the expanding renewable energy sector, it is anticipated that hydrogen energy storage will assume a progressively significant role in grid-balancing and the attainment of a more dependable and sustainable energy supply [124].

Hydrogen energy storage has the potential to assume a pivotal role in the context of distant power generation, particularly in regions where conventional grid connectivity is constrained or unreliable [162]. This technology provides a means to effectively store surplus energy derived from intermittent renewable sources such as solar and wind, enabling its utilization during periods of need. Hydrogen storage has the potential to function as a dependable contingency power solution, guaranteeing an uninterrupted provision of electricity in geographically isolated areas [162]. In regions susceptible to natural calamities, such as hurricanes or wildfires, hydrogen has the potential to serve as an alternative power source in the event of grid failures. The integration of hydrogen energy storage with other energy storage systems, such as batteries or pumped hydro storage, has the potential to establish a dependable and adaptable remote power system [163]. This integration facilitates the effective management of changes in both variable renewable energy generation and demand.

The scalability of hydrogen energy storage enables it to be adjusted to match the precise energy requirements of a geographically isolated area [164]. The inherent flexibility of this system enables isolated communities and industrial sites to effectively respond and adjust to dynamic energy demands [164]. Hydrogen has notable suitability for extended energy storage, rendering it a viable option for isolated areas characterized by restricted availability of regular energy provision. Nevertheless, it is imperative to acknowledge that there exist various problems and factors to consider in the utilization of hydrogen for distant power generation. These include the expenses associated with electrolysis, storage, and transportation of hydrogen, alongside the implementation of safety precautions and the environmental consequences stemming from hydrogen production [165]. Furthermore, continuous progress is being made in the field of hydrogen technology and infrastructure. It is imperative to assess the suitability of hydrogen energy storage in remote regions on a case-by-case basis.

Conclusion

In summary, hydrogen energy storage exhibits significant potential as a pivotal resolution for achieving a sustainable future. This novel technology possesses the capacity to tackle significant contemporary difficulties, such as the transition to sustainable energy, the mitigation of greenhouse-gas emissions, and the incorporation of renewable energy sources into our existing energy infrastructure. Hydrogen possesses the capability to offer a flexible and expandable solution for energy storage, so facilitating the equilibrium between energy supply and demand, augmenting the stability of the grid, and fostering the expansion of renewable energy sources.

Nevertheless, despite the considerable potential, there exist some obstacles that must be surmounted, encompassing issues like cost-efficiency, the establishment of infrastructure, and the sustainable generation of hydrogen. Furthermore, it is imperative to continuously enhance safety considerations and optimize energy conversion efficiency to establish hydrogen energy storage as a genuinely feasible and ecologically sustainable alternative.

Through continuous study, technological advancements, and substantial expenditures, it is plausible to anticipate the resolution of these obstacles, hence enhancing the feasibility and widespread implementation of hydrogen energy storage in the forthcoming years. In the pursuit of a sustainable and decarbonized energy infrastructure, the use of hydrogen energy storage is expected to assume a crucial position in facilitating the attainment of our environmental and energy objectives. The aforementioned concept holds significant potential in facilitating a transition toward a more environmentally friendly, robust, and enduring energy landscape.

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References

1. Q. Hassan, P. Viktor, T.J. Al-Musawi, B.M. Ali, S. Algburi, H.M. Alzoubi, A.K. Al-Jiboory, A.Z. Sameen, H.M. Salman, M. Jaszczur, The renewable energy role in the global energy transformations. Renew. Energy Focus **48**, 100545 (2024)
2. J. Hwang, K. Maharjan, H. Cho, A review of hydrogen utilization in power generation and transportation sectors: achievements and future challenges. Int. J. Hydrogen Energy **48**(74), 28629–28648 (2023)
3. S.U. Batgi, I. Dincer, A study on comparative environmental impact assessment of thermochemical cycles and steam methane reforming processes for hydrogen production processes. Comput. Chem. Eng. **180**, 108514 (2024)
4. C. Bento, T.F. Lopes, P. Rodrigues, F. Gírio, C. Silva, Biogas reforming as a sustainable solution for hydrogen production: comparative environmental metrics with steam-methane reforming and water electrolysis in the Portuguese context. Int. J. Hydrogen Energy **66**, 661–675 (2024)
5. S.G. Nnabuife, C.K. Darko, P.C. Obiako, B. Kuang, X. Sun, K. Jenkins, A comparative analysis of different hydrogen production methods and their environmental impact. Clean Technol **5**(4), 1344–1380 (2023)
6. B. Azizimehr, T. Armaghani, R. Ghasemiasl, A.K. Nejadian, M.A. Javadi, A comprehensive review of recent developments in hydrogen production methods using a new parameter. Int. J. Hydrogen Energy **72**, 716–729 (2024)
7. F. Qureshi, M. Yusuf, H. Ibrahim, H. Kamyab, S. Chelliapan, C.Q. Pham, D.-V.N. Vo, Contemporary avenues of the hydrogen industry: opportunities and challenges in the eco-friendly approach. Environ. Res. **229**, 115963 (2023)
8. M. Aravindan, V. Hariharan, T. Narahari, A. Kumar, K. Madhesh, P. Kumar, R. Prabakaran, Fuelling the future: a review of non-renewable hydrogen production and storage techniques. Renew. Sustain. Energy Rev. **188**, 113791 (2023)
9. M. El-Shafie, Hydrogen production by water electrolysis technologies: a review. Results Eng. **20**, 101426 (2023)
10. A. Arsad, M. Hannan, A.Q. Al-Shetwi, R. Begum, M. Hossain, P.J. Ker, T.I. Mahlia, Hydrogen electrolyser technologies and their modelling for sustainable energy production: a comprehensive review and suggestions. Int. J. Hydrogen Energy **48**(72), 27841–27871 (2023)
11. Y. Wang, G. Xiao, S. Wang, H. Su, Application of nanomaterials in dark or light-assisted fermentation for enhanced biohydrogen

production: a mini-review. Bioresour. Technol. Rep. **21**, 101295 (2023)
12. N.J. Rubinsin, N.A. Karim, S.N. Timmiati, K.L. Lim, W.N.R.W. Isahak, M. Pudukudy, An overview of the enhanced biomass gasification for hydrogen production. Int. J. Hydrogen Energy **49**, 1139–1164 (2023)
13. N. Wu, K. Lan, Y. Yao, An integrated techno-economic and environmental assessment for carbon capture in hydrogen production by biomass gasification. Resour. Conserv. Recycl. **188**, 106693 (2023)
14. S. Bosu, N. Rajamohan, Recent advancements in hydrogen storage-comparative review on methods, operating conditions and challenges. Int. J. Hydrogen Energy **52**, 352–370 (2024)
15. M. Krichen, Y. Basheer, S.M. Qaisar, A. Waqar, A survey on energy storage: techniques and challenges. Energies **16**(5), 2271 (2023)
16. D. Wang, N. Liu, F. Chen, Y. Wang, J. Mao, Progress and prospects of energy storage technology research: BASED on multidimensional comparison. J Energy Storage **75**, 109710 (2024)
17. I. Samylingam, K. Kadirgama, N. Aslfattahi, L. Samylingam, D. Ramasamy, W. Harun, M. Samykano, R. Saidur, Review on thermal energy storage and eutectic nitrate salt melting point. In IOP Conference Series: Materials Science and Engineering. IOP Publishing (2021)
18. Q. Hassan, A.Z. Sameen, H.M. Salman, M. Jaszczur, A.K. Al-Jiboory, Hydrogen energy future: advancements in storage technologies and implications for sustainability. J Energy Storage **72**, 108404 (2023)
19. F. Qureshi, M. Yusuf, M.A. Khan, H. Ibrahim, B.C. Ekeoma, H. Kamyab, M.M. Rahman, A.K. Nadda, S. Chelliapan, A State-of-The-Art Review on the Latest trends in Hydrogen production, storage, and transportation techniques. Fuel **340**, 127574 (2023)
20. D. Tang, G.-L. Tan, G.-W. Li, J.-G. Liang, S.M. Ahmad, A. Bahadur, M. Humayun, H. Ullah, A. Khan, M. Bououdina, State-of-the-art hydrogen generation techniques and storage methods: a critical review. J. Energy Storage **64**, 107196 (2023)
21. B.S. Zainal, P.J. Ker, H. Mohamed, H.C. Ong, I. Fattah, S.A. Rahman, L.D. Nghiem, T.I. Mahlia, Recent advancement and assessment of green hydrogen production technologies. Renew. Sustain. Energy Rev. **189**, 113941 (2024)
22. S.O. Bade, O.S. Tomomewo, A. Meenakshisundaram, P. Ferron, B.A. Oni, Economic, social, and regulatory challenges of green hydrogen production and utilization in the US: a review. Int. J. Hydrogen Energy (2023). https://doi.org/10.1016/j.ijhydene.2023.08.157
23. I. Rolo, V.A. Costa, F.P. Brito, Hydrogen-based energy systems: current technology development status, opportunities and challenges. Energies **17**(1), 180 (2023)
24. F. Zhang, P. Zhao, M. Niu, J. Maddy, The survey of key technologies in hydrogen energy storage. Int. J. Hydrogen Energy **41**(33), 14535–14552 (2016)
25. M.L. Murray, E.H. Seymour, R. Pimenta, Towards a hydrogen economy in Portugal. Int. J. Hydrogen Energy **32**(15), 3223–3229 (2007)
26. I. Iordache, A.V. Gheorghe, M. Iordache, Towards a hydrogen economy in Romania: statistics, technical and scientific general aspects. Int. J. Hydrogen Energy **38**(28), 12231–12240 (2013)
27. U.Y.J.E. Qazi, Future of hydrogen as an alternative fuel for next-generation industrial applications; challenges and expected opportunities. Energies **15**(13), 4741 (2022)
28. A. Oni, K. Anaya, T. Giwa, G. Di Lullo, A. Kumar, Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions. Energy Conv. Manage. **254**, 115245 (2022)
29. H. Ozcan, R.S. El-Emam, B.A. Horri, Thermochemical looping technologies for clean hydrogen production–current status and recent advances. J. Clean. Prod. **382**, 135295 (2022)
30. E. Daneshvar, R.J. Wicker, P.-L. Show, A. Bhatnagar, Biologically-mediated carbon capture and utilization by microalgae towards sustainable CO2 biofixation and biomass valorization–a review. Chem. Eng. J. **427**, 130884 (2022)
31. I. Dincer, C. Zamfirescu, Sustainable energy systems and applications, in *District Energy Systems*. (Springer Science and Business, Boston, MA, 2011), pp.389–429
32. S. Sharma, S.K. Ghoshal, Hydrogen the future transportation fuel: From production to applications. Renew. Sustain. Energy Rev. **43**, 1151–1158 (2015)
33. J.M. Ogden, Review of small stationary reformers for hydrogen production. Report to the international energy agency. 2001. **609**
34. S.D. Angeli, G. Monteleone, A. Giaconia, A.A. Lemonidou, State-of-the-art catalysts for CH4 steam reforming at low temperature. Int. J. Hydrogen Energy **39**(5), 1979–1997 (2014)
35. R. Kothari, D. Buddhi, R. Sawhney, Comparison of environmental and economic aspects of various hydrogen production methods. Renew. Sustain. Energy Rev. **12**(2), 553–563 (2008)
36. M. Amin, H.H. Shah, A.G. Fareed, W.U. Khan, E. Chung, A. Zia, Z.U. Farooqi, C. Lee, Hydrogen production through renewable and non-renewable energy processes and their impact on climate change. Int. J. Hydrogen Energy **47**(77), 33112–33134 (2022)
37. T.N. Do, H. Kwon, M. Park, C. Kim, Y.T. Kim, J.J.E.C. Kim, Carbon-neutral hydrogen production from natural gas via electrified steam reforming: Techno-economic-environmental perspective. Energy Convers Manag. **279**, 116758 (2023)
38. L. Samylingam, N. Aslfattahi, C.K. Kok, K. Kadirgama, N. Sazali, M. Schmirler, D. Ramasamy, W.S.W. Harun, M. Samykano, A. Veerendra, Green engineering with nanofluids: elevating energy efficiency and sustainability. J. Adv. Res. Micro Nano Eng. **16**(1), 19–34 (2024)
39. N. Chalkiadakis, E. Stamatakis, M. Varvayanni, A. Stubos, G. Tzamalis, T.J.E. Tsoutsos, A new path towards sustainable energy transition: techno-economic feasibility of a complete hybrid Small Modular Reactor/Hydrogen (SMR/H2) energy system. Energies **16**(17), 6257 (2023)
40. A. Oni, K. Anaya, T. Giwa, G. Di Lullo, A. Kumar, Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions. Energy Convers. Manage. **254**, 115245 (2022)
41. F.R. Hawkes, I. Hussy, G. Kyazze, R. Dinsdale, D.L. Hawkes, Continuous dark fermentative hydrogen production by mesophilic microflora: principles and progress. Int. J. Hydrogen Energy **32**(2), 172–184 (2007)
42. R. Chaubey, S. Sahu, O.O. James, S. Maity, A review on development of industrial processes and emerging techniques for production of hydrogen from renewable and sustainable sources. Renew. Sustain. Energy Rev. **23**, 443–462 (2013)
43. N. Martinez-Perez, S. Cherryman, G.C. Premier, R.M. Dinsdale, D.L. Hawkes, F.R. Hawkes, G. Kyazze, A.J. Guwy, The potential for hydrogen-enriched biogas production from crops: scenarios in the UK. Biomass Bioenerg. **31**(2–3), 95–104 (2007)
44. I. Dincer, C. Acar, A review on clean energy solutions for better sustainability. Int. J. Energy Res. **39**(5), 585–606 (2015)
45. A. Guwy, R. Dinsdale, J. Kim, J. Massanet-Nicolau, G. Premier, Fermentative biohydrogen production systems integration. Biores. Technol. **102**(18), 8534–8542 (2011)
46. Y. Wang, Y. Liu, Z. Xu, K. Yin, Y. Zhou, J. Zhang, P. Cui, S. Ma, Y. Wang, Z.J.R. Zhu, S.E. Reviews, A review on renewable energy-based chemical engineering design and optimization. Renew. Sustain. Energy Rev. **189**, 114015 (2024)

47. C. Zhu, C. Hu, J. Wang, Y. Chen, Y. Zhao, Z. Chi, A precise microalgae farming for CO2 sequestration: a critical review and perspectives. Sci. Total. Environ. **901**, 166013 (2023)
48. P. Srivastava, E. García-Quismondo, J. Palma, C. González-Fernández, Coupling dark fermentation and microbial electrolysis cells for higher hydrogen yield technological competitiveness and challenges. Int. J. Hydrogen Energy (2023). https://doi.org/10.1016/j.ijhydene.2023.04.293
49. B. Ramprakash, P. Lindblad, J.J. Eaton-Rye, A.J.R. Incharoensakdi, S.E. Reviews, Current strategies and future perspectives in biological hydrogen production: a review. Renew. Sustain. Energy Rev. **168**, 112773 (2022)
50. C. Hitam, A.A. Jalil, A review on biohydrogen production through photo-fermentation of lignocellulosic biomass. Biomass Conv. Bioref. **13**(10), 8465–8483 (2023)
51. C. Putatunda, M. Behl, P. Solanki, S. Sharma, S.K. Bhatia, A. Walia, R.K. Bhatia, Current challenges and future technology in photofermentation-driven biohydrogen production by utilizing algae and bacteria. Int. J. Hydrogen Energy **48**(55), 21088–21109 (2023)
52. A. Ahmad, K. Rambabu, S.W. Hasan, P.L. Show, F. Banat, Biohydrogen production through dark fermentation: Recent trends and advances in transition to a circular bioeconomy. Int. J. Hydrogen Energy **52**, 335–357 (2024)
53. A. Yuvaraj, D. Santhanaraj, A systematic study on electrolytic production of hydrogen gas by using graphite as electrode. Mater. Res. **17**, 83–87 (2014)
54. A.S. Emam, M.O. Hamdan, B.A. Abu-Nabah, E. Elnajjar, A review on recent trends, challenges, and innovations in alkaline water electrolysis. Int. J. Hydrogen Energy **64**, 599–625 (2024)
55. A. Hodges, S. Renz, F. Lohmann-Richters, A. Al-Musawi, A. Jupke, W. Lehnert, G.F. Swiegers, G.G. Wallace, Critical analysis of published physical property data for aqueous potassium hydroxide. collation into detailed models for alkaline electrolysis. J. Chem. Eng. Data **68**(7), 1485–1506 (2023)
56. D.M. Santos, C.A. Sequeira, J.L. Figueiredo, Hydrogen production by alkaline water electrolysis. Quim. Nova **36**, 1176–1193 (2013)
57. A.L. Santos, M.-J. Cebola, D.M. Santos, Towards the hydrogen economy—a review of the parameters that influence the efficiency of alkaline water electrolyzers. Energies **14**(11), 3193 (2021)
58. M.F. Ahmad Kamaroddin, N. Sabli, T.A. Tuan Abdullah, S.I. Siajam, L.C. Abdullah, A. Abdul Jalil, A. Ahmad, Membrane-based electrolysis for hydrogen production: a review. Membranes **11**(11), 810 (2021)
59. A. Aricò, S. Siracusano, N. Briguglio, V. Baglio, A. Di Blasi, V. Antonucci, Polymer electrolyte membrane water electrolysis: status of technologies and potential applications in combination with renewable power sources. J. Appl. Electrochem. **43**, 107–118 (2013)
60. T. Egeland-Eriksen, A. Hajizadeh, S. Sartori, Hydrogen-based systems for integration of renewable energy in power systems: achievements and perspectives. Int. J. Hydrogen Energy **46**(63), 31963–31983 (2021)
61. J. Koponen, A. Kosonen, V. Ruuskanen, K. Huoman, M. Niemelä, J. Ahola, Control and energy efficiency of PEM water electrolyzers in renewable energy systems. Int. J. Hydrogen Energy **42**(50), 29648–29660 (2017)
62. S. Biswas, G. Kaur, G. Paul, S. Giddey, A critical review on cathode materials for steam electrolysis in solid oxide electrolysis. Int. J. Hydrogen Energy **48**(34), 12541–12570 (2023)
63. A. Hauch, R. Küngas, P. Blennow, A.B. Hansen, J.B. Hansen, B.V. Mathiesen, M.B. Mogensen, Recent advances in solid oxide cell technology for electrolysis. Science **370**(6513), eaba6118 (2020)
64. M. Younas, S. Shafique, A. Hafeez, F. Javed, F.J.F. Rehman, An overview of hydrogen production: current status, potential, and challenges. Fuel **316**, 123317 (2022)
65. G. Chisholm, T. Zhao, L. Cronin, Hydrogen from water electrolysis, in *Storing Energy*. (Elsevier, 2022), pp.559–591
66. S.S. Kumar, H. Lim, An overview of water electrolysis technologies for green hydrogen production. Energy Rep. **8**, 13793–13813 (2022)
67. Q. Hassan, V.S. Tabar, A.Z. Sameen, H.M. Salman, M. Jaszczur, A review of green hydrogen production based on solar energy; techniques and methods. Energy Harvest. Syst. (2023). https://doi.org/10.1515/ehs-2022-0134
68. S.S. Kumar, H. Lim, Recent advances in hydrogen production through proton exchange membrane water electrolysis–a review. Sustain. Energy Fuels **7**(15), 3560–3583 (2023)
69. A. Besha, M. Tsehaye, G. Tiruye, A. Gebreyohannes, A. Awoke, R. Tufa, Deployable membrane-based energy technologies: the ethiopian prospect. Sustainability. **12**, 8792 (2020)
70. J.D. Holladay, J. Hu, D.L. King, Y. Wang, An overview of hydrogen production technologies. Catal. Today **139**(4), 244–260 (2009)
71. R. Shah, Pelletization and gasification of waste feedstock for syngas production, University of South-Eastern Norway (2023)
72. V. Ram, S.R.J.E. Salkuti, An overview of major synthetic fuels. Energies **16**(6), 2834 (2023)
73. P. Cavaliere, Hydrogen applications, in *Water Electrolysis for Hydrogen Production*. (Springer, 2023), pp.653–727
74. J.A. Okolie, S. Nanda, A.K. Dalai, F. Berruti, J.A. Kozinski, A review on subcritical and supercritical water gasification of biogenic, polymeric and petroleum wastes to hydrogen-rich synthesis gas. Renew. Sustain. Energy Rev. **119**, 109546 (2020)
75. C. Higman, S. Tam, Advances in coal gasification, hydrogenation, and gas treating for the production of chemicals and fuels. Chem. Rev. **114**(3), 1673–1708 (2014)
76. P.K. Ghodke, A.K. Sharma, A. Jayaseelan, K. Gopinath, Hydrogen-rich syngas production from the lignocellulosic biomass by catalytic gasification: a state of art review on advance technologies, economic challenges, and future prospectus. Fuel **342**, 127800 (2023)
77. B.J.N.F. Bigot, Preparation for assembly and commissioning of ITER. Nucl. Fusion. Fusion **62**(4), 042001 (2022)
78. D. Clery, A piece of the sun: the quest for fusion energy. Abrams (2014)
79. N. R. Council, An assessment of the prospects for inertial fusion energy. National Academies Press. (2013)
80. J. Holdren, Safety and environmental aspects of fusion energy. Annu. Rev. Energy Environ. **16**(1), 235–258 (1991)
81. J. Parisi, J. Ball, The future of fusion energy. World Scientific (2019)
82. E.G. Carayannis, J. Draper, Reviewing fusion energy to address climate change by 2050. **47**(1/2), 1–46. (2021)
83. T. S. Carter, R. Baalrud, T. Betti, Ellis, J. Foster, C. Geddes, A. Gleason, C. Holland, P. Humrickhouse, and C. Kessel, Powering the future: Fusion & plasmas. 2020, US Department of Energy (USDOE), Washington, DC (United States). Office of
84. Board, S.S., E. National academies of sciences, and medicine, progress toward implementation of the 2013 Decadal survey for solar and space physics: A midterm assessment. National Academies Press (2020)
85. S. Imran, M. Hussain, Emerging trends in water splitting innovations for solar hydrogen production: analysis, comparison, and economical insights. Int. J. Hydrogen Energy **77**, 975–996 (2024)
86. M.J. Molaei, Recent advances in hydrogen production through photocatalytic water splitting: a review. Fuel **365**, 131159 (2024)

87. Y. Zhao, Z. Niu, J. Zhao, L. Xue, X. Fu, J. Long, Recent advancements in photoelectrochemical water splitting for hydrogen production. Electrochem. Energy Rev. **6**(1), 14 (2023)
88. A.V. Raghu, T. Tachikawa, Ceramic materials for photocatalytic/photoelectrochemical fuel generation, in *Conversion of water and CO2 to fuels using solar energy: science technology and materials*. (Wiley, NY, 2024), pp.285–307
89. S. Nishioka, F.E. Osterloh, X. Wang, T.E. Mallouk, K. Maeda, Photocatalytic water splitting. Nat. Rev. Methods Prim. **3**(1), 42 (2023)
90. H. Khan, M.U.H. Shah, Modification strategies of TiO2 based photocatalysts for enhanced visible light activity and energy storage ability: a review. J. Environ. Chem. Eng. **11**, 111532 (2023)
91. N. AbouSeada, M.G. Elmahgary, S.O. Abdellatif, K. Kirah, Synergistic integration of zirconium-based metal-organic frameworks and graphitic carbon nitride for sustainable energy solutions: a comprehensive review. J. Alloy. Compd. **1002**, 175325 (2024)
92. S. Chandrasekaran, J.S. Chung, E.J. Kim, S.H. Hur, Advanced nano-structured materials for photocatalytic water splitting. J. Electrochem. Sci. Technol. **7**(1), 1–12 (2016)
93. S. Saeidi, A. Sápi, A.H. Khoja, S. Najari, M. Ayesha, Z. Kónya, B.B. Asare-Bediako, A. Tatarczuk, V. Hessel, F.J. Keil, Evolution paths from gray to turquoise hydrogen via catalytic steam methane reforming: Current challenges and future developments. Renew. Sustain. Energy Rev. **183**, 113392 (2023)
94. N. Hassan, A. Jalil, S. Rajendran, N. Khusnun, M. Bahari, A. Johari, M. Kamaruddin, M. Ismail, Recent review and evaluation of green hydrogen production via water electrolysis for a sustainable and clean energy society. Int. J. Hydrogen Energy (2023). https://doi.org/10.1016/j.ijhydene.2023.09.068
95. P. Nikolaidis, A. Poullikkas, A comparative overview of hydrogen production processes. Renew. Sustain. Energy Rev. **67**, 597–611 (2017)
96. E.Y. Badawi, R.A. Elkharsa, E.A. Abdelfattah, Value proposition of bio-hydrogen production from different biomass sources. Energy Nexus **10**, 100194 (2023)
97. W. Chen, T. Li, Y. Ren, J. Wang, H. Chen, Q. Wang, Biological hydrogen with industrial potential: Improvement and prospection in biohydrogen production. J. Clean. Prod. **387**, 135777 (2023)
98. J. Knaster, A. Moeslang, T. Muroga, Materials research for fusion. Nat. Phys. **12**(5), 424–434 (2016)
99. L. El-Guebaly, Managing fusion radioactive materials: Approaches and challenges facing fusion in the 21st century. Fusion Sci. Technol. **79**(8), 919–931 (2023)
100. W.C. Ng, C.S. Yaw, S.N.A. Shaffee, N.A. Abd Samad, Z.K. Koi, M.N. Chong, Elevating the prospects of green hydrogen (H2) production through solar-powered water splitting devices: a systematic review. Sustain. Mater. Technol. **40**, e00972 (2024)
101. O.F. Aldosari, I. Hussain, Z. Malaibari, Emerging trends of electrocatalytic technologies for renewable hydrogen energy from seawater: recent advances, challenges, and techno-feasible assessment. J. Energy Chem. **80**, 658–688 (2023)
102. T. Ikuerowo, S.O. Bade, A. Akinmoladun, B.A. Oni, The integration of wind and solar power to water electrolyzer for green hydrogen production. Int. J. Hydrogen Energy (2024). https://doi.org/10.1016/j.ijhydene.2024.02.139
103. D. Singh, S. Kumawat, A. Saini, P. Sonia, A. Goyal, G. Sravanthi, K.K. Saxena, S. Shaik, V. Raja, C.A. Saleel, Water splitting via electrocatalysis and photocatalysis: engineering stumbling blocks and advancements. Int. J. Hydrogen Energy **68**, 867–884 (2024)
104. M. Zoback, D. Smit, Meeting the challenges of large-scale carbon storage and hydrogen production. Proc. Natl. Acad. Sci. **120**(11), e2202397120 (2023)
105. R. Kotagodahetti, K. Hewage, F. Razi, R. Sadiq, Comparative life cycle environmental and cost assessments of renewable natural gas production pathways. Energy Convers. Manage. **278**, 116715 (2023)
106. Z. Medghalchi, O. Taylan, A novel hybrid optimization framework for sizing renewable energy systems integrated with energy storage systems with solar photovoltaics, wind, battery and electrolyzer-fuel cell. Energy Convers. Manage. **294**, 117594 (2023)
107. B. Yang, R. Zhang, Z. Shao, C. Zhang, The economic analysis for hydrogen production cost towards electrolyzer technologies: current and future competitiveness. Int. J. Hydrogen Energy **48**(37), 13767–13779 (2023)
108. J. Tang, C. Su, Z. Shao, Advanced membrane-based electrode engineering toward efficient and durable water electrolysis and cost-effective seawater electrolysis in membrane electrolyzers. Exploration (2024). https://doi.org/10.1002/EXP.20220112
109. S.K. Dash, S. Chakraborty, D. Elangovan, A brief review of hydrogen production methods and their challenges. Energies **16**(3), 1141 (2023)
110. M.A. Hossain, M.R. Islam, M.A. Hossain, M. Hossain, Control strategy review for hydrogen-renewable energy power system. J. Energy Storage **72**, 108170 (2023)
111. S. Ren, X. Feng, Y. Wang, Emergy evaluation of the integrated gasification combined cycle power generation systems with a carbon capture system. Renew. Sustain. Energy Rev. **147**, 111208 (2021)
112. N. Nirmala, G. Praveen, S. AmitKumar, P. SundarRajan, A. Baskaran, P. Priyadharsini, S. SanjayKumar, S. Dawn, K.G. Pavithra, J. Arun, A review on biological biohydrogen production: outlook on genetic strain enhancements, reactor model and techno-economics analysis. Sci. Total. Environ. **896**, 165143 (2023)
113. M. Gottardo, J. Dosta, C. Cavinato, S. Crognale, B. Tonanzi, S. Rossetti, D. Bolzonella, P. Pavan, F. Valentino, Boosting butyrate and hydrogen production in acidogenic fermentation of food waste and sewage sludge mixture: a pilot scale demonstration. J. Clean. Prod. **404**, 136919 (2023)
114. E. Carayannis, M. Vinzenzi, J. Draper, N. Kanellos, Can fusion be the next general-purpose technology? Theory, policy, practice, and politics perspectives on stewarding fusion energy research. J. Knowl. Econ.Knowl. Econ. **15**(2), 1–18 (2023)
115. D. Cohen-Tanugi, R. Delaporte-Mathurin, M. Handley, S. Meschini, A. Maris, T. Mouratidis, J. Mullen, A. Seltzman, M. Stapelberg, M. Short, enabling commercial fusion: venture & technology opportunities for a growing fusion industry. (2024)
116. L.M. Amoo, R.L. Fagbenle, An integrated impact assessment of hydrogen as a future energy carrier in Nigeria's transportation, energy and power sectors. Int. J. Hydrogen Energy **39**(24), 12409–12433 (2014)
117. F. Franzoni, M. Milani, L. Montorsi, V. Golovitchev, Combined hydrogen production and power generation from aluminum combustion with water: analysis of the concept. Int. J. Hydrogen Energy **35**(4), 1548–1559 (2010)
118. X. Yu, N.S. Sandhu, Z. Yang, M. Zheng, Suitability of energy sources for automotive application–a review. Appl. Energy **271**, 115169 (2020)
119. I. Hadjipaschalis, A. Poullikkas, V. Efthimiou, Overview of current and future energy storage technologies for electric power applications. Renew. Sustain. Energy Rev. **13**(6–7), 1513–1522 (2009)
120. P. Hoffmann, Tomorrow's Energy, revised and expanded edition: Hydrogen, Fuel Cells, and the Prospects for a Cleaner Planet. MIT press (2012)
121. B. Widera, Renewable hydrogen implementations for combined energy storage, transportation and stationary applications. Therm. Sci. Eng. Prog. **16**, 100460 (2020)
122. P. Ahmadi, A. Khoshnevisan, Dynamic simulation and lifecycle assessment of hydrogen fuel cell electric vehicles considering

various hydrogen production methods. Int. J. Hydrogen Energy **47**(62), 26758–26769 (2022)

123. L.M. Gandia, G. Arzamedi, P.M. Diéguez, Renewable hydrogen technologies: production, purification, storage, applications and safety. Newnes (2013)
124. E. Wolf, Large-scale hydrogen energy storage, in *Electrochemical energy storage for renewable sources and grid balancing*. (Elsevier, 2015), pp.129–142
125. Q. Wang, M. Xue, B.-L. Lin, Z. Lei, Z. Zhang, Well-to-wheel analysis of energy consumption, greenhouse gas and air pollutants emissions of hydrogen fuel cell vehicle in China. J. Clean. Prod. **275**, 123061 (2020)
126. R. Borup, J. Meyers, B. Pivovar, Y.S. Kim, R. Mukundan, N. Garland, D. Myers, M. Wilson, F. Garzon, D. Wood, Scientific aspects of polymer electrolyte fuel cell durability and degradation. Chem. Rev. **107**(10), 3904–3951 (2007)
127. S. Koohi-Kamali, V. Tyagi, N. Rahim, N. Panwar, H. Mokhlis, Emergence of energy storage technologies as the solution for reliable operation of smart power systems: a review. Renew. Sustain. Energy Rev. **25**, 135–165 (2013)
128. G. Jeerh, M. Zhang, S. Tao, Recent progress in ammonia fuel cells and their potential applications. J. Mater. Chem. A **9**(2), 727–752 (2021)
129. P.D. Lund, J. Lindgren, J. Mikkola, J. Salpakari, Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew. Sustain. Energy Rev. **45**, 785–807 (2015)
130. D.O. Akinyele, R.K. Rayudu, Review of energy storage technologies for sustainable power networks. Sustain. Energy Technol. Assess. **8**, 74–91 (2014)
131. R.B. Schainker, Executive overview: energy storage options for a sustainable energy future. In IEEE Power Engineering Society General Meeting, 2004. IEEE (2004)
132. J. Andrews, B. Shabani, Re-envisioning the role of hydrogen in a sustainable energy economy. Int. J. Hydrogen Energy **37**(2), 1184–1203 (2012)
133. N. Shakeri, M. Zadeh, J.B. Nielsen, Hydrogen fuel cells for ship electric propulsion: moving toward greener ships. IEEE Electrific. Mag. **8**(2), 27–43 (2020)
134. R. Estevez, F.J. López-Tenllado, L. Aguado-Deblas, F.M. Bautista, A.A. Romero, D. Luna, Current research on green ammonia (nh3) as a potential vector energy for power storage and engine fuels: a review. Energies **16**(14), 5451 (2023)
135. D. Andriani, Y. Bicer, A review of hydrogen production from onboard ammonia decomposition: Maritime applications of concentrated solar energy and boil-off gas recovery. Fuel **352**, 128900 (2023)
136. G. Chehade, I. Dincer, Progress in green ammonia production as potential carbon-free fuel. Fuel **299**, 120845 (2021)
137. M. Aziz, A.T. Wijayanta, A.B.D. Nandiyanto, Ammonia as effective hydrogen storage: a review on production, storage and utilization. Energies **13**(12), 3062 (2020)
138. H. Ishaq, C. Crawford, Review and evaluation of sustainable ammonia production, storage and utilization. Energy Convers. Manage. **300**, 117869 (2024)
139. C. Smith, A.K. Hill, L. Torrente-Murciano, Current and future role of Haber-Bosch ammonia in a carbon-free energy landscape. Energy Environ. Sci. **13**(2), 331–344 (2020)
140. G. Li, Z. Ma, J. Zhao, J. Zhou, S. Peng, Y. Li, B. Wang, Research progress in green synthesis of ammonia as hydrogen-storage carrier under 'hydrogen 2.0 economy.' Clean Energy **7**(1), 116–131 (2023)
141. M. Asif, S.S. Bibi, S. Ahmed, M. Irshad, M.S. Hussain, H. Zeb, M.K. Khan, J. Kim, Recent advances in green hydrogen production, storage and commercial-scale use via catalytic ammonia cracking. Chem. Eng. J. **473**, 145381 (2023)
142. N.-E. Laadel, M. El Mansori, N. Kang, S. Marlin, Y. Boussant-Roux, Permeation barriers for hydrogen embrittlement prevention in metals–a review on mechanisms, materials suitability and efficiency. Int. J. Hydrogen Energy **47**(76), 32707–32731 (2022)
143. O. Faye, J. Szpunar, U. Eduok, A critical review on the current technologies for the generation, storage, and transportation of hydrogen. Int. J. Hydrogen Energy **47**(29), 13771–13802 (2022)
144. S.A. Gorji, Challenges and opportunities in green hydrogen supply chain through metaheuristic optimization. J. Comput. Design Eng. **10**(3), 1143–1157 (2023)
145. C. Acar, I. Dincer, Hydrogen Energy, in *Comprehensive energy systems*. (Elsevier, The Netherlands, 2018), pp.568–605
146. M. Aziz, Liquid hydrogen: a review on liquefaction, storage, transportation, and safety. Energies **14**(18), 5917 (2021)
147. B. Soltani, N.-E. Benchouia, Fuel cells and hydrogen storage: challenges facing vehicle manufacturers. Int. J. Sci. Res. Eng. Technol. (IJSET) **10**, 10–18 (2019)
148. H. Lee, J. Haider, M.A. Qyyum, C. Choe, H. Lim, An innovative high energy efficiency–based process enhancement of hydrogen liquefaction: energy, exergy, and economic perspectives. Fuel **320**, 123964 (2022)
149. J.O. Ighalo, P.B. Amama, Recent advances in the catalysis of steam reforming of methane (SRM). Int. J. Hydrogen Energy (2023). https://doi.org/10.1016/j.ijhydene.2023.10.177
150. S. Sikiru, T.L. Oladosu, T.I. Amosa, J.O. Olutoki, M. Ansari, K.J. Abioye, Z.U. Rehman, H. Soleimani, Hydrogen-powered horizons: transformative technologies in clean energy generation, distribution, and storage for sustainable innovation. Int. J. Hydrogen Energy **56**, 1152–1182 (2024)
151. E. Sanjaya, A. Abbas, Plasma gasification as an alternative energy-from-waste (EFW) technology for the circular economy: an environmental review. Resour. Conserv. Recycl.. Conserv. Recycl. **189**, 106730 (2023)
152. B.D. Kossalbayev, G. Yilmaz, A.K. Sadvakasova, B.K. Zayadan, A.M. Belkozhayev, G.K. Kamshybayeva, G.A. Sainova, A.M. Bozieva, H.F. Alharby, and T. Tomo, Biotechnological production of hydrogen: Design features of photobioreactors and improvement of conditions for cultivating cyanobacteria. Int. J. Hydrogen Energy 49 (2023)
153. J.A. Luque-Urrutia, T. Ortiz-García, M. Solà, A. Poater, Green energy by hydrogen production from water splitting, water oxidation catalysis and acceptorless dehydrogenative coupling. Inorganics **11**(2), 88 (2023)
154. T. Eklund, A. Fredén, Hydrogen fuel in the domestic maritime transport sector of Fiji: A Feasibility Study (2023)
155. L. Jianlin, L. Guanghui, M. Suliang, S. Jie, An overview on hydrogen energy storage and transportation technology and its typical application in power system. Modern Electric Power **38**(5), 535–545 (2021)
156. M. Ball, M. Wietschel, The future of hydrogen–opportunities and challenges. Int. J. Hydrogen Energy **34**(2), 615–627 (2009)
157. C. Mendez, M. Contestabile, Y. Bicer, Hydrogen fuel cell vehicles as a sustainable transportation solution in Qatar and the Gulf cooperation council: a review. Int. J. Hydrogen Energy (2023). https://doi.org/10.1016/j.ijhydene.2023.04.194
158. D. Akal, S. Öztuna, M.K. Büyükakın, A review of hydrogen usage in internal combustion engines (gasoline-Lpg-diesel) from combustion performance aspect. Int. J. Hydrogen Energy **45**(60), 35257–35268 (2020)
159. S.E. Hosseini, B. Butler, An overview of development and challenges in hydrogen powered vehicles. Int. J. Green Energy **17**(1), 13–37 (2020)
160. D. Wu, D. Wang, T. Ramachandran, J. Holladay, A techno-economic assessment framework for hydrogen energy storage toward multiple energy delivery pathways and grid services. Energy **249**, 123638 (2022)

161. P.T. Moseley, Electrochemical energy storage for renewable sources and grid balancing. Newnes (2014)
162. M. McPherson, N. Johnson, M. Strubegger, The role of electricity storage and hydrogen technologies in enabling global low-carbon energy transitions. Appl. Energy **216**, 649–661 (2018)
163. M.S. Javed, D. Zhong, T. Ma, A. Song, S. Ahmed, Hybrid pumped hydro and battery storage for renewable energy based power supply system. Appl. Energy **257**, 114026 (2020)
164. P. Colbertaldo, S.B. Agustin, S. Campanari, J. Brouwer, Impact of hydrogen energy storage on California electric power system: Towards 100% renewable electricity. Int. J. Hydrogen Energy **44**(19), 9558–9576 (2019)
165. A.I. Osman, N. Mehta, A.M. Elgarahy, M. Hefny, A. Al-Hinai, A.H. Al-Muhtaseb, D.W. Rooney, Hydrogen production, storage, utilisation and environmental impacts: a review. Environ. Chem. Lett. (2022). https://doi.org/10.1007/s10311-021-01322-8

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