

# Green Hydrogen Revolution: Technological Developments and Environmental Evaluations

Sanjeevani B. Murari<sup>1,\*</sup>, Dipali V. Patil<sup>2</sup>

## Abstract

*As a major fuel source for the future, hydrogen energy has received great support from the public, government, and business community. Two significant barriers to cleaning hydrogen commercialization are the high cost of production and the slow expansion of the infrastructure. Numerous hydrogen production techniques are classified using color codes; the most popular option is green hydrogen, which is produced using sustainable resources like solar and wind energy. Green hydrogen consumption is expected to skyrocket across several industries. This review thoroughly examines the primary hydrogen generation systems' costs, environmental effects, and technological development. Recent statistics validate the increased efficiency, cost-effectiveness, and scalability of green hydrogen-generating systems. The advantages, disadvantages, and technological readiness of several novel hydrogen production systems are highlighted. An extensive overview of the hydrogen energy landscape is given in this study. While the anion exchange membrane (AEM) and electrified steam methane reforming (ESMR) both exhibit promise, the solid oxide electrolysis cell (SOEC) now performs better. This specific focus adds significantly to the body of research and deepens our understanding of hydrogen as a possible energy source.*

**Keywords:** Green hydrogen, biomass, electrolysis, hydrogen, pyrolysis, renewable energy

## INTRODUCTION

As global warming worsens, greenhouse gas (GHG) emissions have increased to their highest point ever recorded in history [1], posing an existential threat to humanity. Burning fossil fuels for energy is the main human activity contributing to the growth of greenhouse gases, especially carbon dioxide. The temperature increased because the GHGs trapped solar heat. Thus, attempting to keep the increase in temperature to 1.5°C pre-industrial levels is one of the key objectives of the 2015 Paris Agreement [2]. Thus, nations worldwide have concluded that reducing carbon emissions is necessary to stop the negative impacts of climate change, including rising sea levels, heat waves, frequent wildfires and floods, destruction of coral reefs, and droughts. Because renewable energy is a plentiful and constantly

renewed natural resource, switching to it has been suggested as one of several alternatives for a sustainable future. Renewable energy sources, such as solar, hydro, wind, biomass, and biogas, are not depleted and do not have long-term negative consequences on the environment. Sustainable energy requires energy efficiency, conservation, and renewable energy sources to mitigate climate change and save the environment. Hydrogen exhibits significant promise as a vital component of an energy system that is secure, economical, and clean in the future. The adaptability of hydrogen allows it to increase the output of clean electricity sources, such as wind and solar. Recent technological advancements include solar

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photovoltaics (PV), wind turbines, and electric vehicles (EVs). Policies have demonstrated the ability to develop the international renewable energy sector. Clean hydrogen is receiving considerable attention and support as more international initiatives and regulations are being created. This is because hydrogen has a multitude of uses and applications, and the ability to address several energy-related issues, including lowering emissions, especially in sectors such as long-distance transportation, chemicals, and iron and steel.

As a safe and dependable energy source for energy storage and transportation, hydrogen can aid the decarbonization of the energy sector. This can lessen our dependency on fossil fuels and increase the resilience of the energy supply. As hydrogen is socially, ecologically, and economically viable, it adheres to the principles of environmental, social and governance (ESG). However, there are several obstacles to the clean and broad use of hydrogen in the global energy transition [3], one of which is the sluggish development of the hydrogen infrastructure, which hinders widespread acceptance. Furthermore, the cost of manufacturing hydrogen using low-carbon energy is exorbitant, and coal and natural gas account for nearly all hydrogen produced.

## **METHODOLOGY**

This review used government records and academic databases to investigate the recent developments in green hydrogen production. With an emphasis on well-established techniques such as electrolysis using renewable energy, this study emphasizes the promise of green hydrogen as a sustainable and clean substitute. However, ongoing technical advancements are necessary for cost reduction and increased efficiency. Widespread adoption depends on international cooperation and policy assistance.

The assessment notes shortcomings, even though it focuses on known techniques, such as ignoring potentially important developing technologies and the lack of data on resource availability and environmental impact across regions. The analysis recommends concentrating research efforts on new technologies, improving data gathering, encouraging international collaboration, and creating standardized assessment methodologies to address these constraints and hasten the development of green hydrogen. Planning is essential for resource sustainability.

## **THE COLOR SPECTRUM OF HYDROGEN**

Despite being a colorless gas, hydrogen can be distinguished from other gases by 13 distinct color codes that correspond to the source or production process. The production of brown, gray, and black hydrogen is a significant contributor to the release of greenhouse gases. Coal and natural gas are two examples of fossil fuels used to manufacture hydrogen. Fossil fuels are used to create gray hydrogen, usually via steam methane reforming (SMR). This process releases carbon dioxide into the environment. Depending on the type of coal used, bituminous coal produces black hydrogen, whereas lignite produces brown hydrogen. Although coal gasification is a very polluting process that releases carbon dioxide and carbon monoxide into the atmosphere, it can also produce hydrogen.

By contrast, green hydrogen is a clean technology that seeks to emit no emissions. With the help of this technology, almost all carbon emissions are eliminated when water is electrolyzed to produce hydrogen using renewable energy sources, such as solar and wind power. However, to date, the production of green hydrogen is more expensive than that of blue hydrogen, most likely because electrolyzed components are more expensive. Green hydrogen gets its name from the fact that it is created by electrolyzing water using renewable energy, which removes carbon emissions. This method converts water into oxygen and hydrogen gases by using electricity. Because it may produce zero emissions and use renewable energy sources, green hydrogen production is the most desirable and promising technology.

## **HYDROGEN AS A RENEWABLE ENERGY RESOURCE**

Hydrocarbons (oxygen, nitrogen, and hydrogen) constitute 70% of matter in the universe. Hydrogen is present in considerable amounts in water and plants. The Sun contains hydrogen. When derived from

water, natural gas, or biomass, hydrogen can be utilized as a clean energy source for power and heat-house dwellings. Hydrogen, the most abundant element in the world, is renowned for its efficiency and renewable nature. Furthermore, it is non-toxic and may result in several future employment prospects.

### Hydrogen Applications

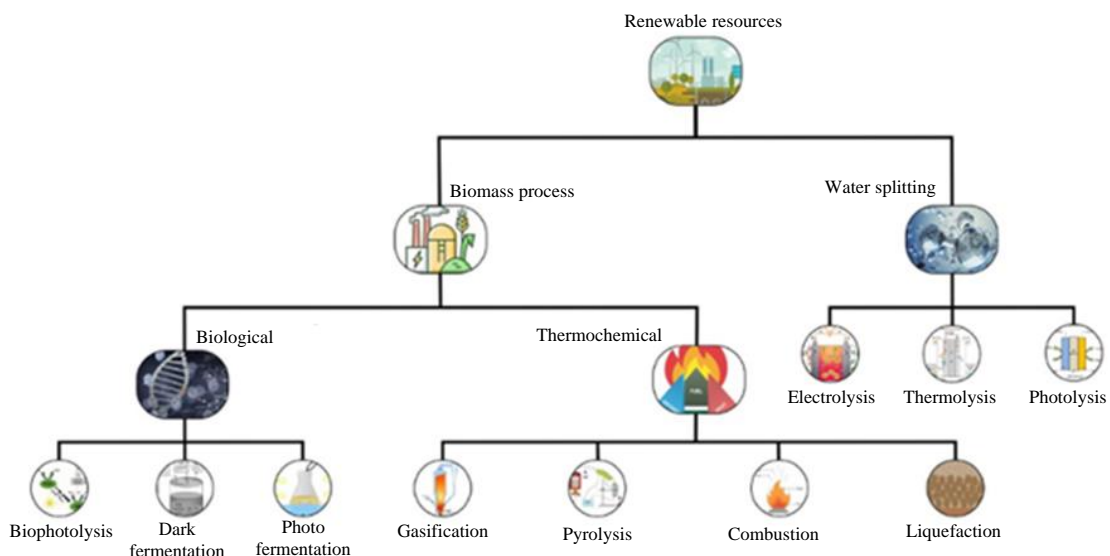
There are numerous uses for hydrogen, including space travel, manufacturing, energy production, and automobiles. In the United States, industry consumes almost all the hydrogen to refine petroleum, process metals, make fertilizer, and prepare food according to the Energy Information Administration (EIA) [4]. Petroleum refineries also use hydrogen to lower the sulfur content in fuels. In the 1950s, the National Aeronautics and Space Administration (NASA) began using liquid hydrogen for the combustibility of rockets. Their potential uses are growing in a variety of industries, such as power generation, fuel cells for EVs, heavy transportation (shipping), manufacturing processes in the steel and cement industries, cleaning products, green ammonia production for fertilizers, electricity grid stabilization, and power generation.

### HYDROGEN PRODUCTION TECHNOLOGIES

Hydrogen can be produced using both renewable and fossil fuels. Green hydrogen is described as hydrogen produced from renewable resources using methods such as biomass processes (biological or thermochemical) and water splitting (electrolysis, thermolysis, and photolysis). The three stages of the biological biomass process are photo fermentation (PF), dark fermentation (DF), and bio-photolysis. The steps in the thermochemical biomass pathway include liquefaction, gasification, combustion, and pyrolysis. Hydrogen has a high heating value (HHV) of 142 MJ/kg and may be used as fuel in steel, chemicals, aircraft, and fuel cells for energy storage.

### Renewable Sources-based Production Technologies

The two main paths that lead to the production of clean hydrogen are water-splitting and biomass-based techniques. Both provide environmentally friendly options; however, their feedstock and processing methods are different. Biomass-related operations use organic materials such as algae or agricultural waste, which are either fermented directly by bacteria or converted into syngas, which are then used to produce more hydrogen. Although these techniques have the potential to be carbon-neutral when managed responsibly, they face efficiency issues and competition for resources, such as water and land. Renewable source-based production technologies are shown in Figure 1.



**Figure 1.** Renewable sources-based production technologies.

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## Water-splitting Technology

The most readily available resource is water, which can be utilized to create hydrogen, which is composed of hydrogen and oxygen. Hydrogen can be extracted from water using three different energy sources: electrolysis, photolysis, and thermolysis.

## Electrolysis

Electrolysis is one of the simplest processes for generating hydrogen from water. This process transforms electrical energy into chemical energy, producing H<sub>2</sub> and O<sub>2</sub> as byproducts. Alkaline-based electrolysis, Proton exchange membrane (PEM), SOEC, and AEM are the four electrolysis technologies shown in Figure 2.

## Recent Green Hydrogen Production Technologies

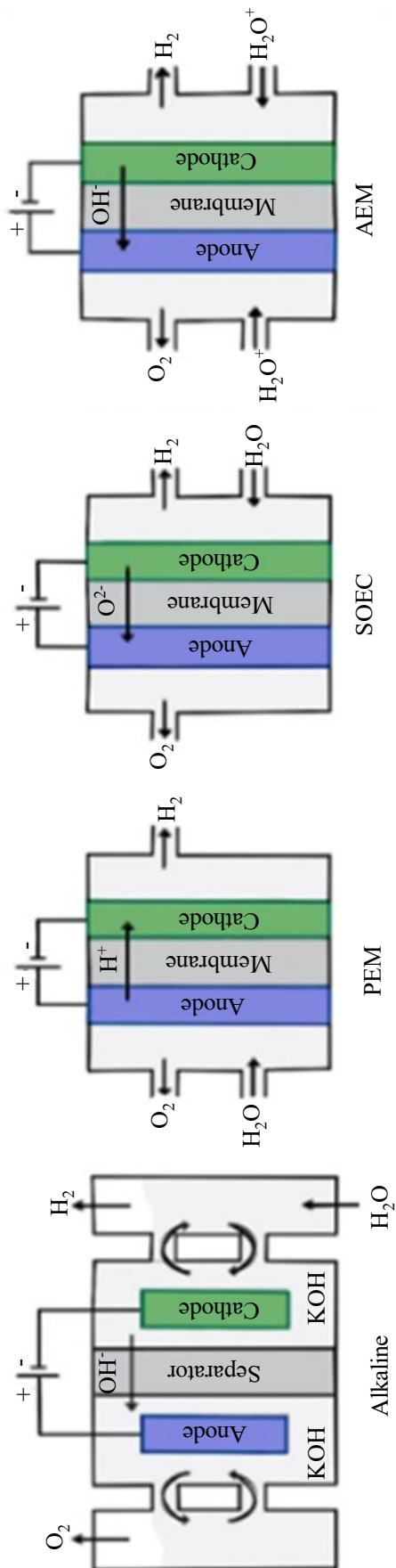
By electrolyzing water to separate its hydrogen and oxygen molecules, green hydrogen can be created using renewable energy sources such as solar and wind power. Water electrolysis is an electrochemical process that uses electricity to divide water into hydrogen and oxygen [5]. This zero-emission technique can be used to produce green hydrogen or hydrogen from renewable electricity sources. To manufacture hydrogen in an environmentally sustainable way, electrolyzed cells can be driven by renewable energy sources, such as solar cells and wind turbines, as well as waste heat from industrial processes [6]. Solid oxide electrolyzers, alkaline, AEM, and PEM are the four water electrolysis technologies that have been created based on their electrolytes, operating conditions, and ionic agents (OH, H<sup>+</sup>, and O<sub>2</sub>) [5, 7]. The concept behind all four systems is the same: water molecules are divided into hydrogen and oxygen using electricity. Compared to PEM and alkaline electrolyzers, which function at lower temperatures, SOECs offer several benefits. SOECs require higher electrochemical reaction rates and less electrical energy to produce hydrogen [8]. Steam and CO<sub>2</sub> can be separated into H<sub>2</sub> and CO using SOECs [9]. Electric heating replaces combustion heating in the primary reformer of an SMR plant by electric heating in electric steam methane reforming (ESMR) [10]. Direct air electrolysis (DAE) can be used to manufacture high-purity green hydrogen from air [11]. Desert-like low humidity levels are suitable for DAE units. Microbial bioelectrochemical systems (BESs) have the capacity to produce energy as well as other value-added products, such as H<sub>2</sub> as shown in Figure 3.

The development of BESs for H<sub>2</sub> production has gained popularity in recent years [12]. A microbial fuel cells (MEC) is a type of BES that can generate H<sub>2</sub> from a variety of organic substrates. Heterotrophic bacteria affixed to an anode are commonly employed by MECs to oxidize organic materials and produce protons and electrons. The protons are converted to H<sub>2</sub> by electrons when they are moved to the cathode. In recent years, green hydrogen production technologies have advanced in several ways, with the potential to increase production scalability, efficiency, and affordability. Green hydrogen currently costs between \$2.50 and \$6.80 per kilogram [13]. However, the cost of green hydrogen is rapidly decreasing because of the combined effects of less expensive renewable energy and lower electrolysis costs.

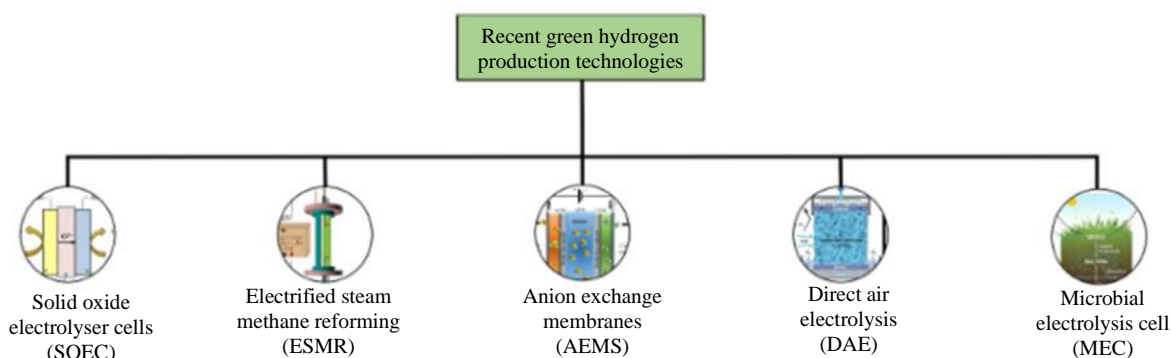
## Potentials and Challenges of Hydrogen Production Technologies

According to some reports, with hydrogen generation processes such as electrolysis, approximately 9 kg of water is needed to produce 1 kg of hydrogen [14]. This may be troublesome in areas where water is scarce. Potential harm to aquatic habitats and higher energy usage are two environmental effects. To solve these issues and make hydrogen production more sustainable, legislation may encourage responsible water usage in the hydrogen business. However, ongoing research intends to develop more water-efficient methods, such as drip irrigation, in agriculture.

Internal combustion engines can run on hydrogen; however, fuel cells are more efficient and produce less nitrogen oxides when using hydrogen. The number of hydrogen-powered vehicles has been restricted by the high cost of fuel cells and the scarcity of hydrogen-fueling facilities. Companies are reluctant to establish refueling stations without a market for hydrogen-fueled vehicles, whereas customers are discouraged from buying hydrogen-fueled automobiles when refueling facilities are not easily accessible.



**Figure 2.** Conceptual setup of four electrolysis cell technologies.



**Figure 3.** Recent green hydrogen production technologies.

The logistics of the distant transport of hydrogen in this form remains a major challenge, even though it can be transported at high temperatures or  $-253^{\circ}\text{C}$  in compressed form as a liquid [15]. Insulation and specialized equipment are required to sustain extremely low temperatures during liquid hydrogen storage.

Extensive efforts are being made to develop technologies that can convert hydrogen generated via electrolysis, which is achieved by external or in situ steam/water electrolysis for the conversion of carbon dioxide into liquid fuels such as ammonia, methanol, diesel, and dimethyl ether (DME).

This would make it easier to move people from places with large amounts of renewable energy to places with less fossil fuels and renewable energy [16]. It is expected that these items will experience multiple fresh deployments as the sector grows. Moreover, because hydrogen is highly flammable and can burn under a variety of circumstances, serious questions have also been raised about its safety [17]. Because hydrogen is colorless, odorless, and lighter than air, leaks are difficult to detect. It is currently very challenging to develop safe and efficient hydrogen storage technologies. Safety hazards may also arise from the need to store gaseous hydrogen at freezing temperatures or high pressures. Therefore, it is necessary to carefully examine safety precautions and laws when creating a robust hydrogen infrastructure that includes production facilities and distribution networks, as well as specialized firefighting equipment and training. Effective use of hydrogen technology requires public education and knowledge of hydrogen safety.

### India's Green Hydrogen Mission: A Clean Energy Leap

With 5 MMT of clean hydrogen produced by 2030 and a potential of 10 MMT, India hopes to become a global leader in this field through its ambitious National Green Hydrogen Mission. The objective was to promote local production, create jobs, and achieve decarbonization through the adoption of green hydrogen in diverse areas.

Focus areas include creating a strong transportation and storage infrastructure, producing clean hydrogen using renewable energy sources, and pushing research to lower costs and increase efficiency.

Collaboration between the government, businesses, and academics is essential for success. India has the capacity to maximize the potential of green hydrogen and lead the global clean energy transition by addressing issues such as cost competitiveness, infrastructure development, and safety regulations.

### MAHARASHTRA GREEN HYDROGEN POLICY 2023: A GLIMPSE

By 2030, the state of Maharashtra is expected to produce 500 kilotons of clean hydrogen annually, which is in line with the objectives of the Maharashtra Green Hydrogen Policy 2023. To do this, the policy provides a number of incentives, such as grants for building hydrogen pipeline infrastructure, exemptions from electricity rates for hydrogen produced on-site, and subsidies for the generation of

hydrogen using renewable energy. In addition, the strategy supports skill development initiatives for the green hydrogen industry and offers incentives for the local production of electrolysis and other equipment. This all-encompassing strategy seeks to benefit a number of stakeholders: the state itself gains from increased employment, improved energy security, and environmental improvements; the industry receives access to clean fuel and possible cost savings; and investors discover appealing opportunities in the developing sector. To ensure the policy's success and open the door to a cleaner, more sustainable future, it will still be necessary to establish a strong hydrogen infrastructure, achieve cost competitiveness with existing fuels, and implement efficient safety standards.

## CONCLUSION

This review provides a comprehensive overview of the progress made globally in green hydrogen production technologies and associated policies, with particular emphasis on electrolysis and the potential of emerging green hydrogen technologies. Green hydrogen has garnered significant attention and investment in various industries owing to its versatility in the manufacturing chain, from renewable electric energy generation to water electrolysis and hydrogen synthesis. Recent efforts have been directed toward developing green hydrogen technologies that rely on renewable energy sources for hydrogen production. These technologies include renewable electrolysis, which utilizes electricity from renewable sources such as solar, wind, or hydro to power the electrolysis process for hydrogen production, and bio-based hydrogen, which employs organic waste and biomass through gasification, fermentation, or pyrolysis. The most developed green hydrogen technique is electrolysis; researchers are essential for the simultaneous advancement of this technology. With further research and development, green hydrogen production systems are expected to become more efficient and cost-effective. Addressing hydrogen challenges and issues requires a multidisciplinary approach involving collaboration between industry, government agencies, researchers, and standards organizations. Additionally, ongoing research and technological advancements are crucial for improving the safety of hydrogen throughout its entire lifecycle, from production to end-use applications. Overcoming these challenges is essential for realizing the potential benefits of green hydrogen in terms of economic growth, environmental sustainability, and energy security. Derived from renewable resources, green hydrogen provides a viable way to decarbonize the energy industry, lowering dependency on fossil fuels, and boosting climate resilience. Significant GHG reductions are made possible by their use in various sectors, supporting environmental sustainability. Green hydrogen's rapidly falling production costs make it an affordable option that is essential for reducing climate change and supporting international sustainability objectives, such as the UN SDGs and ESG principles.

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