Green Hydrogen Production Utilizing Solar Energy and Other Renewable Energy Sources, Addressing Climate Change Mitigation

S. J. Haider, Vijay Kumar Srivastava

***Abstract:** The Industrial Revolution has brought about significant technological and economic progress. Still, it has also led to a notable rise in atmospheric carbon dioxide, which contributes to global warming and climate change. Industrialisation, urbanisation, and agricultural expansion have increased energy demands and raised environmental concerns. In response, clean energy technologies such as solar and wind power are increasingly replacing fossil fuels. India, the third-largest emitter of carbon dioxide and a significant energy consumer, requires a diverse range of renewable energy sources to achieve its decarbonization targets. The transition to sustainable energy involves zero-emissions electricity systems and low-emission carriers, including biogas and hydrogen, as well as electric vehicles. Hydrogen has the potential to decarbonise both the stationery and mobility sectors, including shipping and aviation. To maximise the benefits of green hydrogen, issues related to costs, infrastructure, and scalability must be addressed. Greater support from governments and industry stakeholders for research and development is crucial to making hydrogen technologies more accessible and effective in achieving decarbonization goals.*

***Keywords:** Decarbonization; GHG Emission; Net Zero Emission, Renewable Energy Sources; Green Hydrogen; Production Technology; Storage and Transportation*

Abbreviations:
CCS: Carbon Capture and Storage
GHG: Greenhouse Gas
IEA: International Energy Agency
SMR: Steam Methane Reforming

I. INTRODUCTION

Energy resources are essential for the operation of all economic sectors. Among these, electricity is the most widespread and in-demand form of energy, making a significant contribution to the socioeconomic and technological progress of any country. Additionally, electricity demand usually increases with population growth, especially when it correlates with economic development trends.

The global energy sector is undergoing a transformation to address climate change and enhance energy security. This change is driven by the limited availability of fossil fuels and their adverse environmental effects. Highlighting renewable energy, particularly solar power, presents a significant opportunity to reduce greenhouse gas (GHG) emissions and meet sustainable energy demands [1].

Hydrogen is a colourless gas; however, it is categorised into various "colours" based on the method of production. The main categories include grey, blue, and green hydrogen, along with other types such as black, brown, pink, turquoise, and yellow, which are either currently used or in development. These colour distinctions are important because they indicate the carbon intensity associated with producing hydrogen. The classification system uses colours to show both how the hydrogen is made and the environmental impact involved.

A. Grey Hydrogen represents the most prevalent form of hydrogen production; however, it is characterised by significant carbon emissions, totalling approximately 13 kg CO_2e for each kilogram of Hydrogen produced.
B. Blue Hydrogen utilises carbon capture and storage (CCS) technologies to mitigate emissions, which typically range from 9 to 12 kg CO_2e per kilogram, depending on the efficiency of the CCS system.
C. Green Hydrogen, generated through electrolysis powered by renewable energy sources, stands as a beacon of sustainability in the hydrogen production landscape, resulting in minimal carbon emissions.
D. Turquoise Hydrogen is produced via methane pyrolysis, a process that yields Hydrogen and solid carbon without direct CO_2 emissions, although the carbon intensity may vary.
E. Pink Hydrogen is created through electrolysis driven by nuclear energy, presenting low emissions; however, it does not qualify as a renewable energy source.
F. Black and Brown Hydrogen, derived from coal gasification, are highly polluting and unsustainable options, with associated emissions exceeding 19 kg CO_2e per kilogram.
G. Yellow Hydrogen is produced using electricity sourced from the power grid, with its environmental impact being dependent on the specific energy mix utilised.

The use of fossil fuels to produce hydrogen results in lower purity and higher emissions of greenhouse gases. Hydrogen has a high energy density of 140 MJ/kg, more than double that of typical solid fuels, which are around 50 MJ/kg [2]. Its chemical energy content is 39.4 kWh/kg, three times higher than that of liquid hydrocarbons at 13.1 kWh/kg [3]. Global hydrogen

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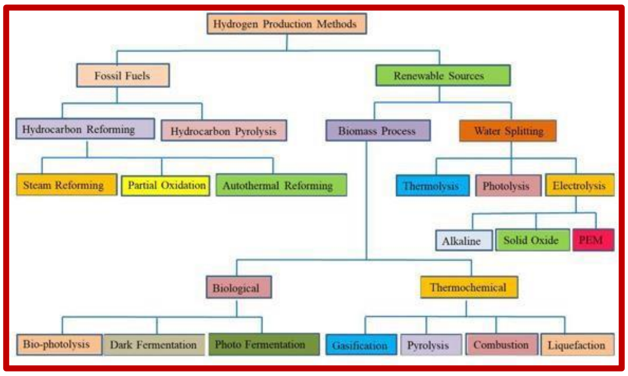
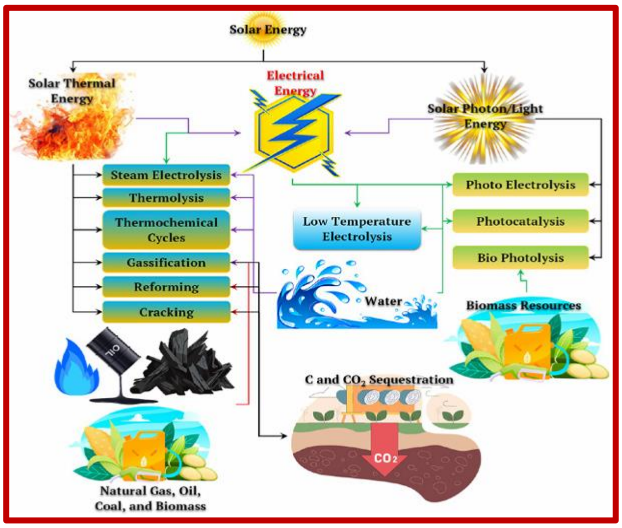
production is roughly 500 billion cubic metres annually [2], with nearly 96% produced from fossil fuels, mainly through the steam reforming of natural gas (methane) [4]. The development of green hydrogen and storage technologies is progressing continuously and gaining popularity, leading to increased demand for hydrogen across various applications (Figs. 1 & 2).



[Fig.1: Hydrogen Production Technologies [5]]



[Fig.2: Schematic Layout Showing Solar Energy-Based Pathways for Hydrogen Production Utilising Water, Fossil Fuels, and Biomass [6]]

Hydrogen has been widely utilised in the energy industry as a fuel for internal combustion engines. Since the mid-20th century, it has played a vital role in various sectors, especially the oil refining industry. Additionally, it is extensively employed in the production of ammonia, being the primary component of fertilisers [5]. However, its intensive utilisation is evident in oil refining, chemicals such as ammonia and methanol, steel manufacturing, and applications in transportation, buildings, and power systems. Future uses include electricity generated from hydrogen fuel cells,

- To power cars, buses, trucks, ships, and even aircraft,
- Serving as a versatile energy source in the power grid, and
- Providing heating to buildings to reduce CO2 emissions.

Hydrogen exhibits the highest energy density, and is both renewable and environmentally friendly. The two main reasons it has not been widely regarded as a significant fuel for energy consumption are: firstly, it functions primarily as an energy carrier, despite being the most abundant element in water and hydrocarbons; secondly, its low critical temperature of 33°K makes it suitable for both mobile and stationary uses, where its volumetric and gravimetric storage densities become essential. Considering its potential (Fig. 3), the study explores eco-friendly and economically viable methods for its production.

[Fig.3: Opportunities for Scaling up Hydrogen Production [7]]

II. NEED FOR HYDROGEN PRODUCTION

The world faces significant challenges from climate change, mainly due to greenhouse gas emissions. The rising energy demand, driven by urbanisation, industrialisation, and population growth, has placed enormous pressure on the planet [8]. The projected population growth is expected to surpass 10 billion by 2050, resulting in increased energy demands [9]. According to the International Energy Agency (IEA), this rapid pace will continue to cause a temperature rise that could result in irreversible environmental damage [10]. The Global Hydrogen Review 2024 indicates that global hydrogen demand reached a record high in 2023, increasing by 2.5% compared to the previous year. Green hydrogen, produced using renewable energy sources, chiefly relies on water electrolysis as its most advanced production technology [12]. A decline in renewable energy costs lowers the price of green hydrogen, making it easier for industries to adopt the produced hydrogen [13]. The Vision 2050, which emphasises achieving net-zero emissions, highlights the sustainable development of clean energy, with hydrogen recognised as a low-carbon fuel [14]. Hydrogen can generate energy with minimal greenhouse gas emissions; however, current technologies pose challenges. Researchers and industry professionals must develop cost-effective methods for synthesising green hydrogen from renewable sources, along with efficient storage and transportation solutions.

A. Hydrogen Production Methods

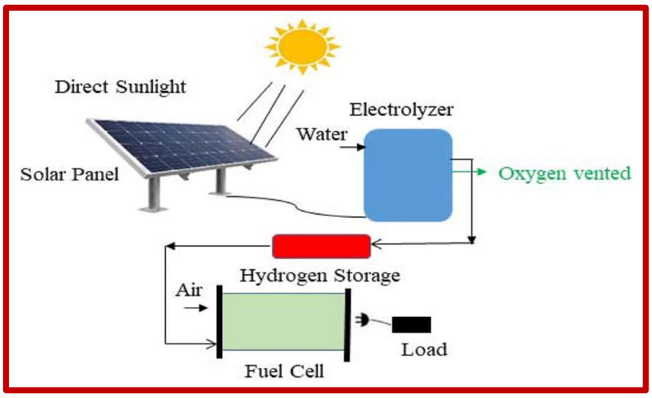
Globally, hydrogen production primarily relies on fossil fuels, while alternative sources remain relatively minor contributors, primarily due to the decreasing costs of renewable energy sources. The growing role of hydrogen in electricity generation is now enabling a transition to alternative production methods [15]. Moreover, there is significant potential for converting hydrogen into ammonia and other feedstocks, which have broader applications within existing infrastructure than hydrogen alone [16]. The different methods of hydrogen production are summarised in Figure 1. Currently, direct hydrogen production from renewable sources is unfeasible; therefore, a hybrid and efficient approach for hydrogen extraction is essential [17]. This process is expected to considerably reduce greenhouse gas emissions associated with hydrogen production from fossil fuels [18].

B. Hydrogen Production from Renewable Energy Sources

Hydrogen is the most abundant gas and serves as an eco-friendly fuel since its energy production mainly releases heat and water, with lower GHG emissions [19]. It is used in the petroleum and chemical industries [20]. Currently, hydrogen is primarily produced through fossil fuel-based thermochemical processes, such as coal gasification, hydrocarbon reforming, plasma reforming, and pyrolysis [21]. Future research should focus on generating hydrogen from natural organic waste, possibly using photocatalysts [22], via photoelectrochemical water splitting [23], which holds commercial promise. Global demand for pure hydrogen—essential in refining, ammonia synthesis, and other fields—is increasing, with approximately 95 million tonnes produced today, primarily from natural gas (76%) and coal (22%) [7]. Hydrogen is increasingly viewed as a key future fuel for transportation and energy sectors [24]. Many studies confirm its technological feasibility [25] and environmental compatibility [26]. Scaling up existing technologies can enhance production efficiency, lower costs through the use of renewable energy [27], and depend on the availability of raw materials and infrastructure [28]. The process relies on efficient production, storage, transportation, and safety standards [29]. In addition to fossil fuels, renewable energy sources have experienced significant improvements recently [30]. Despite challenges in commercialising hydrogen from renewables, ongoing research shows promising signs of future viability. Primary uses include hydro-treatment and hydrocracking in refineries, as well as ammonia and methanol synthesis, and steel manufacturing via direct reduction [7]. Although most current production relies on fossil fuels, which raises environmental concerns, these methods are unsustainable [9], and resources are depleting rapidly [31]. Renewable energy contributes a small share to hydrogen production, with ongoing efforts to develop eco-friendly, pollution-free methods [32]. Advances in biomass, solar, and wind energies have led to more efficient hydrogen production techniques with higher yields [33].

C. Solar to Hydrogen

Solar energy is considered the most promising resource to fulfil the world's current and future energy needs [34]. Recent fluctuations in oil and natural gas prices have significantly decreased the cost of renewable energy [35]. The ability of solar power to generate inexpensive electricity presents opportunities for economic growth via hydrogen, a clean alternative fuel [36]. Moreover, advancements in solar storage technologies enhance the reliability and efficiency of converting solar energy into hydrogen [37]. A critical factor in solar-to-hydrogen systems is the overall conversion efficiency (see Fig. 4). This efficiency can be further enhanced by modifying solar panels to boost hydrogen output while lowering costs.

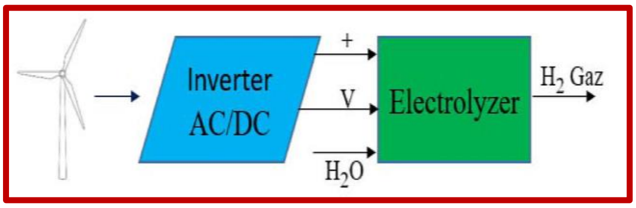


[Fig.4: Hydrogen Production Tapping Solar Energy [8]]

III. WIND TO HYDROGEN

In an electrolyser, wind energy is employed to split water molecules into hydrogen and oxygen. Earlier research indicated that hydrogen production systems powered by hybrid renewable sources, such as wind and solar, are most effective when combined with wind energy (Fig. 5). As societal demand for renewables increases, costs are decreasing, leading to enhanced capacity for all alternative energy sources. The rapid development of these technologies is encouraging expanded use of various renewables, contributing to climate change mitigation.

In recent years, there has been increased focus on utilising renewable resources, especially wind energy, for sustainable power generation. This energy source is also seen as a reliable option for hybrid power systems, which help deliver clean and dependable energy [38]. However, wind energy can pose challenges and uncertainties, prompting the use of energy storage systems in conjunction with wind power dispatch [39]. Standard energy storage methods include Lithium-ion batteries [40], converting electricity to gas [41], and converting electricity to hydrogen [42], which support applications ranging from fuel cell vehicles to industrial processes [43]. Among hydrogen production methods from fossil fuels, water electrolysis, which achieves efficiencies over 75%, is a well-established and mature technology [44].



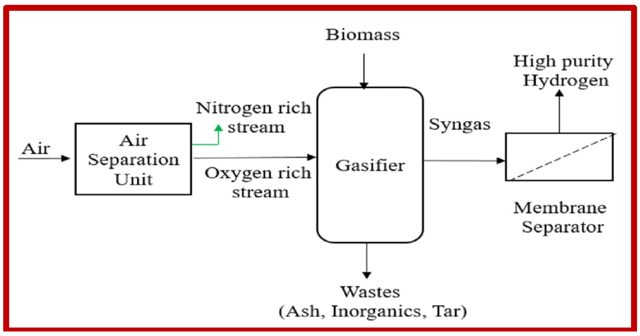
[Fig.5: Hydrogen Production Tapping Wind Energy [8]]

A. Biomass to Hydrogen

Biomass remains the primary renewable energy source used for power, and its use continues [45]. It is derived from materials such as agricultural produce, wood, plants, animal waste, and municipal solid waste, offering a cost-effective, eco-friendly, and sustainable alternative to fossil fuels [46].

Research has predominantly focused on lignocellulosic biomass, including wood, agricultural residues, and energy crops, employing thermochemical methods such as gasification and pyrolysis [47]. The approach also includes biological processes, such as anaerobic digestion, where microorganisms produce biogas in oxygen-limited environments. Renewable resources can be further harnessed to convert one form of energy into another useful product. For example, hydrogen, which is valuable in the industrial, power, transport, and fuel sectors, can be produced from renewable sources [48]. Currently, most hydrogen is derived from fossil fuels, with Steam Methane Reforming (SMR) being the most economical large-scale method [49]. Less than 5% of hydrogen production utilises renewable energy, primarily through water electrolysis, and no large-scale hydrogen production from biomass currently exists [50].

Thermochemical conversion of biomass, encompassing gasification, liquefaction, and pyrolysis, appears to be a well-established technology with promising prospects for future applications (Fig. 6). Gasification, in particular, is a cost-effective technique for producing renewable hydrogen, achieving nearly 50% process efficiency, with potential for further improvement.



[Fig.6: Hydrogen Production Through Biomass [51]]

IV. CONCLUSION

Urbanisation and the increasing human population have greatly influenced global energy needs. Relying on non-renewable fossil fuel infrastructure leads to issues such as air pollution, CO2-driven global warming, greenhouse gas emissions, acid rain, depletion of energy resources, and environmental harm, all of which contribute to climate change. These challenges underscore the importance of developing renewable energy sources. Hydrogen, as an efficient carrier of energy, is emerging as a promising alternative fuel to fulfil energy demands. Green hydrogen, produced with zero carbon emissions, has attracted significant scientific interest recently. This review examines hydrogen production from renewable resources, including biomass, solar, wind, geothermal, and algae, as well as traditional non-renewable sources such as natural gas, coal, nuclear, and thermochemical processes. It is also crucial to perform an economic analysis of hydrogen production from each source before selecting the suitable technology. Additionally, the environmental impacts of all hydrogen generation methods should be highlighted. Future studies may explore various materials, reactors, and industrial applications of these technologies to inform stakeholders in research and development within the hydrogen sector.

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DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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AUTHOR'S PROFILE

S. J. Haider is a senior IAS officer from the 1991 batch of the Gujarat cadre. With a strong academic background in physics and decades of dedicated service, he has been entrusted with crucial leadership roles in multiple departments. Currently, he serves as the Additional Chief Secretary of the Energy & Petrochemicals Department, Government of Gujarat. His administrative journey reflects his versatility and commitment across various industries, including education, energy, and governance. His in-depth analytical training in science refined his logical and problem-solving skills, which later enabled him to excel in administration and policy-making. His extensive service record across education, industry, energy, rural development, and transportation speaks to his administrative skills. His career is a testament to the impact that dedicated public servants can have on the development and governance. His leadership in the Energy and Petrochemicals Department is particularly significant with the growing focus on renewable energy, sustainable practices, and industrial innovation. His strategic vision ensures that the state remains at the forefront of these developments, addressing both economic and environmental priorities. He played a key role in the formulation of several government policies in Gujarat, including the IT Policy, Electronics Policy, Tourism Policy, Student Start-up & Innovation Policy 2.0, and the State Action Plan on Climate Change. Attended several International Conferences like COP-21 (Paris, 2015), COP-27 (Egypt, 2022), COP-29 (Baku, 2024), New York Climate Week (NYC, 2024), etc. He played a crucial role in organising landmark programs, including the Vibrant Gujarat Global Summit (2024), the launch of Mission LiFE (2022), and RE-Invest by the MNRE (2024), among others. He is a recipient of the Best Collector's Award, Kaushalyacharya Award, Census Medal, Award for the Promotion of Start-ups, etc.

Professor Vijay Kumar Srivastava is the former Vice Chancellor of Maharaja Sayajirao University of Baroda. Before joining MS University, he had served as Vice Chancellor of Indus University, Ahmedabad, and Sankalchand Patel University, Visnagar. He is also a member of the State Environmental Impact Assessment Authority. Dr. Srivastava has held several key positions in various universities over the years. These include the GSFC University, Vadodara, and the Pandit Deendayal Energy University, among other esteemed institutions. In addition to his administrative experience in educational institutions, he has authored several research papers and publications to his credit. He has expertise in wastewater treatment, solid waste management, environmental issues related to industries, and energy recovery using plasma technology.