ELECTROLYZING THE FUTURE: GREEN HYDROGEN AND THE RENEWABLE ENERGY SHIFT

Dr Mousumi Bhattacharjee James, Associate Professor, Applied Chemistry
New Horizon Institute of Technology and Management, Thane
University of Mumbai, India.
mbjames1@gmail.com
mousumijames@nhitm.ac.in

Abstract-The paradigm shift of transitioning to renewable energy with least environmental impact is no longer a moral option—it is a strategic necessity for planetary survival to shift to energy systems with near-zero greenhouse gas emissions, reduced air and water pollution, energy independence and resilience, sustainable economic growth and job creation.The message of climate change is loud and clear, and the pressure to transition to cleaner, renewable energy sources has shifted from being just a moral imperative to a global prerequisite for life and existence. The rapidly growing global population and industrialization has significantly increased the greenhouse gases (GHGs) emissions, indicating a temperature rise of 3–6 °C by 2050 (1).The urgent need to transition toward clean, renewable energy has evolved from an ethical choice to a critical global demand. Though there is an array of options for renewable energy and work is in progress in all sectors, this paper focuses primarily on Green hydrogen an emerging trailblazer renewable energy source—not just for its clean credentials, Zero Carbon Emissions, and accepted as the cleanest energy carriers available today but, various other virtues which this energy source displays, like it can store excess renewable energy and release it when needed, it can back heavy industries unlike various other sources, it can balance supply-demand fluctuations, stabilize grids with high renewable penetration and enable seasonal energy storage, unlike batteries which are short-term. The global scalability & abundance of green hydrogen is known, as Hydrogen is the most abundant element in the universe. With growing investments and falling costs of electrolysers, green hydrogen is becoming economically viable, with renewable energy potential and is

establishing itself as a pillar of net-zero strategies worldwide.

Keywords: Green hydrogen, Sustainability, Zero Carbon, Greenhouse gases, Renewable energy

I. INTRODUCTION

The message of climate change is loud and clear, and the pressure to transition to cleaner, renewable energy sources has shifted from being just a moral imperative to a global prerequisite for life and existence. The rising ocean temperatures, diminishing glaciers, polluted urban air, and unprecedented storms are stark reminders that time is running out. The rapidly growing global population and industrialization has significantly increased the greenhouse gases (GHGs) emissions, indicating a temperature rise of 3–6 °C by 2050 (1) . A very recent review paper offers a comprehensive review of hydrogen as a clean alternative fuel, specifically analyzing the challenges and opportunities in its production, storage, and transportation(2). With the latest release of the Intergovernmental Panel on Climate Change (IPCC)'s contributions for the sixth climate change assessment report, strong statements have been made on the role of human activity on global warming**(3).**With that, the IPCC emphasized in the report for reaching at least net-zero CO2 emissions to limit global warming effect. The urgent need to transition toward clean, renewable energy has evolved from an ethical choice to a critical global demand. While traditional renewables like solar, wind, hydro, and geothermal are vastly cleaner than fossil fuels, even these must be optimized to reduce land use, resource extraction, and lifecycle emissions. Recognizing this, governments, industries, and communities are turning to low-carbon alternatives—green hydrogen, solar, wind, geothermal, and hydropower—that produce little or no emissions during generation **(4)(5)** The paradigm shift of transitioning to renewable energy with least environmental impact is no longer a moral option—it is a strategic necessity for planetary survival to shift to energy systems with near-zero greenhouse gas emissions, reduced air and water pollution, energy independence and resilience, sustainable economic growth and job creation. Though, technical innovation is accelerating at a remarkable pace and intensity—delivering not just promise, but proven technologies grounded in science and already making an impact. Yet that does not suffice the global needs.

The World Economic Forum, 2023 report, Fostering Effective Energy Transition, stated that 95% of countries have improved their total Energy Transition Index score (As per UN trade and development, the Energy Transition Index is a score of how well a country is doing in its energy transition. It uses current conditions and how conducive the country is to the future adoption of renewables.) over the past decade, but there has been only "marginal growth" in the past three years. The need for renewable energy innovation has never been as urgent as it is now. Rapid and effective renewable energy innovation is crucial to achieving climate goals.

According to the United Nations, Fossil fuels still account for nearly 60 per cent of electricity generation, but cleaner sources of energy are stepping up. Between 2015 and 2024, annual electricity capacity of renewables increased by around 2,600 gigawatts (GW) - a 140 per cent increase. In the same period, fossil fuel electricity capacity only increased by around 640 GW (16 per cent). Renewables are now the cheapest and most accessible energy option in many regions, and could supply up to 90% of global electricity by 2050. It could decarbonize 90 per cent of the power sector by 2050, massively cutting carbon emissions and helping to mitigate climate change. **(6)**

Though there is an array of options for renewable energy and work is in progress in all sectors, this paper focuses primarily on Green hydrogen an emerging trailblazer renewable energy source—not just for its clean credentials, Zero Carbon Emissions, and accepted as the cleanest energy carriers available today but various other virtues which this energy source displays, like it can store excess renewable energy and release it when needed, it can back heavy industries unlike various other sources, it can balance supply-demand fluctuations, stabilize grids with high renewable penetration and enable seasonal energy storage, unlike batteries which are short-term. The global scalability & abundance of green hydrogen is known as Hydrogen is the most abundant element in the universe. With growing investments and falling costs of electrolysers, green hydrogen is becoming economically viable, scalable across regions with renewable energy potential and is establishing itself as a pillar of net-zero strategies worldwide. Moreover countries can produce green hydrogen domestically, reducing reliance on imported fossil fuels and enhancing energy sovereignty. As per the Ministry of New and Renewable energy, India has announced a target of energy independence by 2047 and a net-zero by 2070. Green Hydrogen is expected to play a substantial role towards achieving these goals.

II. OVERVIEW OF GREEN HYDROGEN

Hydrogen has emerged as a promising energy source for a cleaner and more sustainable future due to its clean-burning nature, versatility, and high energy content. Moreover, hydrogen is an energy carrier with the potential to replace fossil fuels as the primary source of energy in various industries **(7)**. Fossil fuels pose a threat to the environment and living systems on the planet. These fuels lead to an increase in the CO2 content in the atmosphere that causes global warming and undesirable climatic changes. Additionally, these are limited sources of energy which are not renewable and eventually will diminish from the earth. There is huge urge of identifying and utilizing the renewable energy resources to replace these fossil fuels in the near future as it is expected to have no impact on environment and thus would enable one to provide energy security **(8).**To produce hydrogen, it must be separated from the other elements in the molecules where it occurs. Hydrogen can be produced from many different sources in different ways to use as a fuel. The two most common methods for producing hydrogen are steam-metha*ne reforming* and *electrolysis* (splitting water with electricity). Researchers are exploring other hydrogen production methods, or pathways. Hydrogen is primarily produced through steam methane reforming, which produces significant greenhouse gas emissions and limits the potential of hydrogen as a clean energy source. Green hydrogen is hydrogen gas produced through the electrolysis of water, powered entirely by renewable energy sources such as solar and wind. This carbon-neutral process differentiates green hydrogen from other forms of hydrogen that rely on fossil fuels. By utilizing renewable energy, green hydrogen eliminates greenhouse gas emissions, positioning itself as a key component in the transition to a sustainable energy future. By harnessing abundant renewable resources, green hydrogen promises to bridge the gap between energy demand and environmental responsibility. No emissions occur. Significant investment and advancements in renewable hydrogen production through electrolysis are necessary to overcome this limitation. There is also a growing demand for hydrogen infrastructure, including hydrogen refueling stations and storage and transportation systems, which are crucial for the growth and success of the hydrogen industry. The future of hydrogen as a part of the global energy mix will depend on continued investment and commitment to develop and commercialize this promising energy source.

As per world economic forum**(9)** the article highlights the aspects of why we need green hydrogen. They continued to focus on Green hydrogen as a critical enabler of the global transition to sustainable energy and net zero emissions economies. There is unprecedented momentum around the world to fulfil hydrogen's longstanding potential as a clean energy solution. It was stated out where things with hydrogen stand now and how it can help to achieve a clean, secure and affordable energy future.

A review on critical perspectives of green hydrogen**(10)** examines the state of GH2 (green hydrogen) research production technologies for integrating into renewable energy systems. Green hydrogen was produced via electrolysis powered by renewable energy, in the study GH2 showed significant potential to decarbonize at the same time it enhanced grid stability, and supported the Power-to-X paradigm, which interlinks electricity, heating, transportation, and industrial applications. Though still, widespread adoption faces many challenges, which includes high production costs, infrastructure constraints, and the requirement for robust regulatory frameworks. The study noted that addressing these barriers would require advancements in electrolyzer efficiency, scalable fuel cell technologies, and efficient storage solutions. They extended that sector-coupled smart grids incorporating hydrogen demonstrate the potential to integrate GH2 into energy systems, enhancing renewable energy utilization and ensuring system reliability. Economic analyses predict that GH2 can achieve cost parity with fossil fuels by 2030 and will play a primary role in low-carbon energy systems by 2050. The ability of green hydrogen to convert surplus renewable electricity into clean energy carriers positions it as a deciding factor for decarbonizing energy-intensive sectors, such as industry, transportation, and heating. This study further emphasized on the transformative potential of green hydrogen in creating a sustainable future for energy systems.Green hydrogen can accelerate the transition to carbon-neutral energy systems by addressing technical, economic, and policy challenges and through coordinated efforts in innovation and infrastructure development, and thus contribute to achieving global climate goals.

III. HYDROGEN TYPES: WHAT IS GREEN HYDROGEN?

The element Hydrogen that exists in gaseous form can be produced through a variety of methods. The commonest method of hydrogen production is steam methane reforming, which involves the reaction of natural gas with high-temperature steam to produce hydrogen and carbon dioxide. Hydrogen can also be produced from renewable energy sources like wind, solar, and water through electrolysis **(11) (12)** .The colors of hydrogen refer to the method of production and their environmental impact. Hydrogen can be categorized by the adopted method for its production and further the carbon emissions associated, as per this the categorized types are:

- Grey hydrogen: This is produced from natural gas or coal through steam reforming, releasing significant carbon dioxide (CO_2) emissions. (which is fossil fuel-based with high emissions)
- Blue hydrogen: Also produced from fossil fuels but with the addition of carbon capture and storage (CCS) to mitigate CO_2 emissions, making it a cleaner option than grey hydrogen.
- Green hydrogen (which is produced with renewable energy and has zero emissions). The uniqueness of Green hydrogen is due to the fact that its production process uses renewable energy from sources like solar or wind for electrolysis to split water, which in turn ensures that it is a clean, with zero-emission energy source which supports a low-carbon future.

IV. GREEN HYDROGEN'S ROLE IN THE ENERGY TRANSITION

Green hydrogen has the potential to substantially contribute to the global energy transition toward sustainable and decarbonized energy systems. Produced through renewable-powered electrolysis, green hydrogen provides a viable pathway for decarbonizing challenging sectors, such as heavy industry and transportation, while simultaneously addressing renewable intermittency by enabling large-scale energy storage and grid flexibility. A study **(13)** states that Green hydrogen stands out due to its fundamentally different, and more sustainable, production method:

Renewable Energy Source: It is powered by renewable energy, meaning it does not rely on fossil fuels or produce greenhouse gases. A recent study**(14)** emphasized on the perspective and relationship between hydrogen as a green fuel and renewable energy, as well as the economics of hydrogen supply considering the steadily declining costs of renewables and the role of hydrogen in energy transport

Electrolysis Process: Water is split using electricity in a device called an electrolyzer, separating hydrogen from oxygen. Recent literature **(15)**states that, the scientific and industrial communities worldwide have achieved impressive technical advances in developing innovative electrocatalysts and electrolysers for water and seawater splitting

Zero Emissions: This process is entirely emissions-free, contributing to decarbonization efforts and a sustainable energy future. Produced using renewable energy via electrolysis, green hydrogen emits only water vapor when used—no greenhouse gases. A recent article emphasizes on the Role of Green Hydrogen in achieving low and net-zero carbon emissions **(16)**

V. PRODUCTION OF GREEN HYDROGEN

Hydrogen can be produced using a number of different processes. Thermochemical processes use heat and chemical reactions to release hydrogen from organic materials, such as fossil fuels and biomass, or from materials like water. Water (H2O) can also be split into hydrogen (H2) and oxygen (O2) using electrolysis or solar energy. Microorganisms such as bacteria and algae can produce hydrogen through biological processes. As stated on the official website of the US Department of energy **(17)** green hydrogen can be produced by a number of processes, namely thermochemical processes using the energy in various resources, such as natural gas, coal, or biomass, to release hydrogen from their molecular structure. In other processes, heat, in combination with closed-chemical cycles, produces hydrogen from feedstocks such as water. Next is the Electrolytic Processes, Electrolyzers use electricity to split water into hydrogen and oxygen. This technology is well developed and available commercially, and systems that can efficiently use intermittent renewable power are being developed. Another important process is Direct Solar Water Splitting Processes. Green hydrogen can also be produced by Biological Processes in which microbes such as bacteria and microalgae can produce hydrogen through biological reactions, using sunlight or organic matter. These technology pathways are in the research and development stage, with pilot demonstrations occurring, but in the long term have the potential for low-carbon hydrogen production.

VI. GREEN HYDROGEN'S VALUE NICHES

Green hydrogen is gaining serious momentum as a clean energy game-changer. The key advantages can be enumerated as:

Zero Carbon Emissions:

Climate Neutral Production: Unlike grey or blue hydrogen, green hydrogen is made without fossil fuels, making it essential for achieving net-zero goals A recent study **(18)** states that as the world seeks to meet climate goals, green hydrogen will play a crucial role in building a cleaner and more resilient energy future.

Suitable for Hard-to-Decarbonize Sectors: Ideal for steel production, chemical manufacturing, and refining—industries where electrification is tough **(19)**

Energy Storage Solution: It can store excess renewable energy (like solar or wind) and release it when needed, helping balance supply and demand. A recent finding demonstrated the cost, challenges, and potential advancements in the green hydrogen storage and transportation field. Further they established that the cost associated with storing and transporting green hydrogen is anticipated to decrease over time due to technological advancements and economies of scale being achieved.**(20)**

Widespread Applications : Usage in Heavy-duty trucks and buses is established, Green hydrogen is Ideal for long-distance travel and heavy payloads, thanks to its high calorific value and shorter refueling times. Used in aviation and shipping**,** Hydrogen-powered planes and ships are the future of clean transportation, reducing emissions in sectors that account for significant global pollution. Also finds usage in Industrial applications, in industries such as steel and cement, green hydrogen is a game-changer for decarbonization. Has possibilities of usage in passenger vehicles**.** While adoption might take longer due to current costs, green hydrogen holds potential for urban mobility in the long term. It finds usage as clean transportation as it can power fuel cells in heavy-duty vehicles, ships, and trains, offering a low-emission alternative to diesel

Job Creation: Sparks new opportunities in the green economy—from electrolyzer manufacturing to infrastructure development. Green hydrogen is emerging as a powerful engine for job creation, with countries like India aiming to generate a large number of jobs in this sector. Studies enumerate that growth in the hydrogen and fuel cell industries will lead to vast new employment opportunities, and these will be created in a wide variety of industries, skills, tasks, and earnings.**(21)** Many of these jobs do not currently exist and do not have occupational titles defined in official classifications.

VII. PITFALLS AND LIMITATIONS

Despite its promise, green hydrogen still faces challenges like high production costs and infrastructure needs. But with global investment and innovation ramping up, it's poised to play a starring role in the clean energy transition.Though urgent action is needed to limit global warming to 1.5 °C above pre-industrial levels, various fuels are being weighed against each other. A study conducted has exhibited various aspects in this pretext about **(1)** Hydrogen, with its high energy density and compatibility with renewable energy systems, which presents a promising clean energy solution to mitigate GHGs emissions. Yet, its widespread adoption faces challenges such as high production costs, limited infrastructure, and an underdeveloped value chain. At present, approximately 96% of global hydrogen production relies on fossil fuels, contributing to substantial emissions, while only 4% comes from water electrolysis. Green hydrogen, produced via electrolysis with 55–80% efficiency, remains expensive at $2.28–7.39/kg, compared to grey hydrogen at $0.67–1.31/kg, which generates 8.5 kg CO_2 per kg of hydrogen production. Hydrogen's low density poses challenges for storage, while transportation risks and insufficient infrastructure create further obstacles. The lack of global standards and investment uncertainties further impede the development of a comprehensive hydrogen economy.While green hydrogen is the most environmentally friendly, its production is currently more expensive and requires significant investment in renewable energy and electrolysis infrastructure.

VIII. CONCLUSION

Green hydrogen is much more than just a clean fuel—it's a huge impetus for economic transformation, energy independence, and environmental assistance. As globally many nations race to decarbonize, this versatile energy source offers significant benefits to climate action and job creation. From powering industries to empowering communities, green hydrogen holds the promise of a future where sustainability and prosperity go hand in hand. For researchers, it presents a dynamic frontier—where electrochemical breakthroughs, systems integration, and policy remodeling can shape a low-carbon future. Beyond its technical promise, green hydrogen unfolded a multidimensional framework for sustainable and inclusive growth, with the potential to catalyze new industries and employment ecosystems. As global momentum accelerates, the research community has a pivotal role to deepen understanding, drive newer solutions, and ensure that the transition is not only sustainable, inclusive and future-proof.The challenge now is not just to harness its potential, but to build the ecosystems—technological, financial, and human—that will make green hydrogen thrive.

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