GREEN HYDROGEN: AN ALTERNATIVE CLEAN ENERGY FOR SUSTAINABLE FUTURE

M. Chakraborty
Sarsuna College, Kolkata-700061, West Bengal, India
Email: cmahua99@gmail.com

To Cite this Article
M. Chakraborty, "Green Hydrogen: An Alternative Clean Energy For Sustainable Future", Journal of Science Engineering Technology and Management Science, Vol. 02, Issue 07, July 2025,pp: 611-616, DOI: http://doi.org/10.64771/jsetms.2025.v02.i07.pp611-616
Submitted: 10-06-2025 *Accepted: 13-07-2025* *Published: 20-07-2025*

ABSTRACT—Green hydrogen has emerged as an alternative potential energy source for a clean and sustainable future. It is versatile, has high energy content and derived from renewable energy sources. It has the potential to replace traditional energy sources like fossil fuels. In this article, we have introduced hydrogen as future energy carrier with its various types and production methods and storage techniques. We also discussed about its various applications and limitations. This study offers perceptions about overcoming the challenges and accelerating the worldwide adoption of carbon-free and sustainable energy source for future generation.

Keywords: Green Hydrogen, renewable energy, carbon-free, sustainable.

I. INTRODUCTION

Energy plays an important role in economic development and social welfare of a country. The most used type of energy is the electrical energy. With the rapid technological development and invention of high-tech appliances, the worldwide demand for energy has been increasing rapidly day by day. In 2023, global demand of electricity reached as high as 29,471 TWh, which is more than 627 TWh (+2.2%) compared to previous year [1]. Fossil fuels [2] like coal, natural gas and oil were used as major source of energy in 20th century. But the fossil fuels have certain drawbacks for eg. limited resource, faster depletion and other harmful effects to the environment [3] like pollution, climate change, global warming, loss of bio-diversity etc by the emission of greenhouse gases (carbon di-oxide and methane).Therefore, researchers in 21st century are exploring sustainable alternative renewable and clean energy sources like solar, wind, hydro etc. The power generation from these renewable sources are discontinuous and inconsistent as most of the sources depend on the atmospheric conditions, like for solar it is the solar intensity and for wind it is the air velocity. So, there is a growing need of an alternative energy source that would supply more continuous and reliable power generation system with an efficient energy storage unit. The intensifying concerns of climate change, resource exhaustion, and environmental degradation have strengthened the worldwide pursuit of clean, sustainable, and low-carbon energy alternatives. Among several promising solutions, green hydrogen, a zero-carbon emitter fuel has gained significant consideration as an echo friendly energy carrier.

Moreover, it aligns closely with some of the United Nations Sustainable Development Goals (SDGs) [4], specifically clean energy (SDG 7), industry innovation (SDG 9), and climate action (SDG 13). Various industries, organizations and governments are increasingly implementing sustainable energy strategies to ensure a continuous energy supply across the globe in future. In order to meet zero carbon targets by mid-century, green hydrogen has been integrated with the energy mix that not only reduces greenhouse gas emissions but also strengthens energy security and fosters economic growth and developments in technology. It has the potential to transform the energy scenery worldwide.

The present paper explores the potential of green hydrogen as an alternative clean energy, investigating its type, production techniques, technological advancements, potential applications, economic viability etc while highlighting the limitations that must be tackled to extend its widespread adoption. With continuous innovation and worldwide coordinated efforts, green hydrogen has emerged as a key element that could play a transformative role in shaping a sustainable, decarbonised future.

II. HYDROGEN: ITS PRODUCTION AND STORAGE

Hydrogen, the most abundant and lightest element in the world could be the possible solution to the existing energy problem as it produces completely carbon free emission. It exists in gaseous form and is the promising eco-friendly alternative to traditional fuel.

2.1 Types of Hydrogen

According to the method of production of hydrogen and the energy source it can be classified as grey hydrogen, blue hydrogen or green hydrogen [5]. Grey and blue are the conventional hydrogen types whereas the green hydrogen is the renewable form. Also there are other hydrogen types.

- Grey Hydrogen: It is the most commonly available form of hydrogen. It is produced from splitting of fossil fuels e.g. natural gas by steam methane reforming (SMR) or auto thermal reforming (ATR) technique. During the process of fabrication, the CO2 is not captured and released into the atmosphere.
- Blue Hydrogen: Blue hydrogen is produced in the same way as grey hydrogen from the fossil fuel by steam methane reforming (SMR) or gasification but here the generated carbon is captured and stored in an environment friendly way [6].
- Green Hydrogen: The most environment friendly yet expensive option is the green hydrogen that uses green energy or renewable energy such as wind or solar power[7] for its production via electrolysis of water [8] which splits water into hydrogen and oxygen.
- Black and brown hydrogen: This is most environmentally harmful product produced by gasification from fossil fuels i.e. black coal and lignite.
- Pink hydrogen: Pink or purple or crimson hydrogen is generated using nuclear energy to power the electrolysis process [9]. As CO2 is not produced during the process therefore this hydrogen is green one [10].
- Turquoise hydrogen: This new category of hydrogen is generated in small scale using methane pyrolysis and carbon and hydrogen are produced in solid form. This method can be a low-emission source of hydrogen if the heating is done by renewable energy and also the produced carbon is either permanently stored or it is used [11].
- Yellow hydrogen: It is also a new category of hydrogen produced by electrolysis using solar energy [12].
- White Hydrogen: This is a naturally occurring type of hydrogen found in deposits below the surfaces.

2.2 Production of Hydrogen and current status:

Hydrogen is abundant in compounds like water (H2O) and hydrocarbons (e.g., methane, CH4), it rarely exists as a free gas on Earth, meaning it must be produced. According to research, it can be produced by number of processes: Steam methane reforming (SMR) or natural gas reforming, Electrolysis, Coal or biomass gasification, Microbial biomass conversion and Thermochemical water splitting cycles. Green hydrogen is produced using renewable energy sources (like solar, wind etc) without CO_2 emission. Primarily water electrolysis is taken place where pure water is split into H_2 (hydrogen) and O_2 (oxygen) using electricity from renewable sources. $2H_2O \dashrightarrow 2H_2 + O_2$

Direct solar water splitting called photolytic processes use light energy to split water into hydrogen and oxygen. This is in fundamental stage of research but it has long term potential for hydrogen production with low environmental impact. Biological processes also produce hydrogen. Microbes like bacteria, microalgae etc produces hydrogen through biological reactions using biomaterials and sunlight.

2.2.1 Water electrolysis

In this process water molecules are split into hydrogen and oxygen by electrical current. This is a promising technique for hydrogen production as it uses only two elements, water and renewable electricity. The chemical equations for electrolysis are [13]:

At anode: $2H_2O$ (liquid) → O_2 (gas) + $4H^+$ (aq) + $4e^-$

Oxygen gas and hydrogen ions are released in the electrolyte solution.

At cathode: $4H^+$ (aq) + $4e^-$ → $2H_2$ (gas)

Here hydrogen gas is generated by the reaction of hydrogen ions with electrons.

Overall reaction: $2H_2O$ (liquid) → $2H_2$ (gas) + O_2 (gas)

2.2.2 Different types of electrolysis technologies:

- Polymer Electrolyte Membrane (PEM): Solid polymer electrolyte membrane is used to separate the electrodes at temperature 50-80 C.
  Advantage: High purity H_2 is obtained. Response is fast and design of electrolyser is compact. Efficiency is high [14], flexible and dynamic response (IEA, 2021). Their scalability allows them to furnish to large scale production of hydrogen.
  Disadvantage: Lifespan is limited, expensive catalysts (Pt) is used.
- Alkaline Electrolysis cells (AEL):Most widespread technology. Aquous KOH/NaOH is used as electrolyte at temperature 60-90 C [15].
  Advantage: Inexpensive and mature technology suitable for smaller scale applications, lifespan is longer.
  Disadvantage: Lower purity and slower response.
- Anion Exchange Membrane (AEM): Solid polymer is used as electrolyte at temperature 40-80 C.
  Advantage: All the benefits of PEM and alkaline
  Disadvantage: Low durability
- Solid Oxide Electrolysis Cells (SOEC):Solid oxide ceramic is used as electrolyte here at high temperature 600-900C.
  Advantage: Efficiency is highest [16]
  Disadvantage: Complex material, Degradation at high temperature, less commercially mature [17]. Scalability is also constrained posing challenges for extensive implementation.

Due to advancements in material science and engineering more efficient and durable electrocatalysts including iridium oxide, nickel-iron alloys, nickel-molybdenum alloys are developed that promotes the electrochemical reaction and reduces the energy losses occurred during the process.

To cope up with the fresh water challenges, seawater electrolysis is also explored, though it suffers major challenges.

2.2.3 Thermochemical water splitting:

In this process water molecules are splitted into hydrogen and oxygen using high temperature heat. This method is a promising technology for production of green hydrogen as it can be powered using renewable sources of heat eg. concentrated solar power, nuclear energy or waste heat from industrial processes [18].The technology is presently in research and development phase. The process of thermochemical water splitting involves several steps including the endothermic reduction of a metal oxide with steam and the exothermic re-oxidation of the reduced metal oxide with air [19]. The overall process can be represented as a series of chemical reactions [19]:

MO + H_2O + energy → M + H_2O (steam) (step-1)

$M + 1/2\ O_2 \rightarrow MO + energy$ (step-2)

$2H_2O + energy \rightarrow 2H_2 + O_2$ (step-3) where MO is metal oxide.

Depending on the specific metal oxide acting as a catalyst, the temperature of the reaction varies from 800-1200 C. The efficiency and the operating conditions are contro;;ed by the specific metal oxides used eg. Ceria (CeO_2),ferrites (MFe_2O_4, where M= Co, Ni or Cu) and perovskites (ABO_3, where A and B are metal ions [20]

Alternate renewable routes of green hydrogen production:

- Photocatalytic water splitting- here sunlight and a semiconductor photocatalyst is used to split water and produce H_2 . Presently efficiency is very low (-1-2%)
- Photoelectrochemical (PEC) cells – It combines photon absorption and electrolysis in a single cell
- Biomass gasification – Agricultural wastes are converted into hydrogen

2.2.3 Storage of Hydrogen

Efficient storage of hydrogen is a major challenge. Due to lower volumetric energy density of hydrogen in comparison to traditional fuels, special storage method is needed for it.

Hydrogen can be stored in three different methods:

- Compressed gas- stored inside tanks under high pressure (350-700 bar), used in fuel cell vehicles, industrial backup systems etc
- Liquified Hydrogen (cryogenic storage) – hydrogen is cooled to -253 C and stored in insulated tanks as a cryogenic liquid, used in aerospace and hydrogen refueling station
- Chemical or material based storage – Hydrogen is absorbed by solid or liquid material
    - Metal Hydrides-here hydrogen reacts with magnesium or lanthanum-nickel alloys
    - Chemical-hydrogen storage-some compounds like ammonia, methanol or formic acid store hydrogen chemically
    - Liquid organic hydrogen carriers (LOHCs)- organic molecules like toluene absorb hydrogen and stable liquid is formed, easier handling and existing infrastructure.
    - For large scale applications underground hydrogen storage in salt caverns is under investigation [21].

Metal-organic frameworks, carbon nanotube structure, advanced hydrides etc could be used as future adsorbent materials for hydrogen storage.

III. APPLICATIONS AND CHALLENGES OF GREEN HYDROGEN:

It can be used as a fuel or feedstock, offering flexibility across a wide range of applications—from fuel cells in transportation to industrial processes like ammonia production, steelmaking etc.

Transportation: Green Hydrogen could be used as fuel for hydrogen fuel cell vehicles (cars, truck, shipping, rail, aviation etc) due to long range and fast refueling time.

Industry: Used in different industries like refining and chemical production

Generation of power: Backup power, balances grid power

Residential heating: used in hydrogen broilers

Despite of its promising applications green hydrogen technology is still in its primitive stages facing several limitations which need to be addressed before its worldwide adoption:

- High production costs:
  Production cost of green hydrogen is 2-6 times high compared to the conventionally produced grey hydrogen derived from fossil fuels. Here expensive electrolysers are used to split water into hydrogen and oxygen. Also it has to be economically competitive with other forms of energy and methods of hydrogen production.
- Lack of Infrastructure:

Storage and transport problems due to low volumetric energy density of hydrogen. Hydrogen requires more space to store. Also special pipelines and delivery trucks are necessary for efficient delivery. The integration of green hydrogen into existing energy systems is challenging due to lack of infrastructure. Moreover regulatory clearances and safety codes and standards are need to be developed and implemented that requires more investment, technological development and regulatory frameworks.

- High demand of water resource:
  The consumption of water, the primary material for electrolysis could be a great concern in regions where water is scarce.
- Limited efficiency:
  Due to certain energy losses involved in the electrolysis process the efficiency does not reach high values.

IV. CONCLUSIONS

Green hydrogen is a promising renewable energy source that has unique characteristics and features. It is clean, emission less, sustainable resource. It's high storage capabilities make it useful for energy storage and grid balancing. Also, as it can be produced in large scale to meet the rising energy demands, it could be said that its scalability is very high. Despite its potential, several challenges need to be taken care of, for its global adoption. In this regard coordination between governments, research institutes and industries are very much essential. Moreover, development of infrastructure and innovation of technology are earnestly required to fulfil the goal.

REFERENCES

[1] International Energy Agency (IEA) report 2024 available at: https://iea.blob.core.windows.net/assets/140a0470-5b90-4922-a0e9-838b3ac6918c/WorldEnergyOutlook2024.pdf

[2] Germanier, R., & Moricciani, N. (2023). Perceiving and adapting to climate change: Perspectives of Tuscan wine-producing agritourism owners. Sustainability, 15(3), 2100.

[3] Ali, S., Dogan, E., Chen, F., & Khan, Z. (2021). International trade and environmental performance in top ten emitters countries: The role of eco-innovation and renewable energy consumption. Sustainable Development, 29(2), 378–387.

[4] https://www.undp.org/sustainable-development-goals

[5] Nikolaidis, P., & Poullikkas, A. (2017) A comparative overview of hydrogen production processes. Renew able and Sustainable Energy Reviews, 67, 597–611.

[6] Yu, M., Wang, K., & Vredenburg, H. (2021). Insights into low-carbon hydrogen production methods: Green, blue and aqua hydrogen. International Journal of Hydrogen Energy, 46(41), 21261–21273.

[7] Gondal, I. A., Masood, S. A., & Khan, R. (2018). Green hydrogen production potential for developing a hydrogen economy in Pakistan. International Journal of Hydrogen Energy, 43(12), 6011–6039.

[8] Proost, J. (2020). Critical assessment of the production scale required for fossil parity of green electrolytic hydrogen. International Journal of Hydrogen Energy, 45(35), 17067–17075.

[9] Nadaleti, W. C., de Souza, E. G., & Lourenço, V. A. (2022). Green hydrogen-based pathways and alternatives: Towards the renewable energy transition in South America's regions–Part B. International Journal of Hydrogen Energy, 47(1), 1–15.

[10] Ajanovic, A., Sayer, M., & Haas, R. (2022). The economics and the environmental benignity of different colors of hydrogen. International Journal of Hydrogen Energy, 47(57), 24136–24154.

[11] Karmaker, S. C., Chapman, A., Sen, K. K., Hosan, S., & Saha, B. B. (2022). Renewable energy path ways toward accelerating hydrogen fuel production: Evidence from global hydrogen modeling. Sus tainability, 15(1), 588.
[12] Newborough, M., & Cooley, G. (2020). Developments in the global hydrogen market: The spectrum of hydrogen colours. Fuel Cells Bulletin, 2020(11), 16–22.
[13] M.D. Rashid, M.K. Al Mesfer, H. Naseem, M. Danish, Hydrogen production by water electrolysis: a review of alkaline water electrolysis, PEM water electrolysis and high temperature water electrolysis, International Journal of Engineering and Advanced Technology (2015).
[14] A.S. Aric`o, 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, Journal of Applied Electrochemistry 43 (2013) 107–118.
[15] A. Buttler, H. Spliethoff, Current status of water electrolysis for energy storage, grid balancing, and sector coupling via power-to-gas and power-to-liquids: a review, Renew. Sustain. Energy Rev. 82 (1) (2018) 2440–2454.
[16] S. Grigoriev, P. Millet, V. Porembsky, Hydrogen production from solid oxide electrolysis: state-of-the-art technology review, Int. J. Hydrog. Energy 46 (1) (2021) 559–573.
[17] https://www.clean-hydrogen.europa.eu/system/files/2014-09/study%2520electrolyser_0-Logos_0_0.pdf
[18] C. Agrafiotis, M. Roeb, C. Sattler, A review on solar thermal syngas production via redox pair-based water/carbon dioxide splitting thermochemical cycles, Renewable and Sustainable Energy Reviews 42 (2015) 254–285.
[19] P. Furler, J. Scheffe, D. Marxer, M. Gorbar, A. Bonk, U. Vogt, A. Steinfeld, Thermochemical CO 2 splitting via redox cycling of ceria reticulated foam structures with dual-scale porosities, Physical Chemistry Chemical Physics 16 (22) (2014) 10503–10511.
[20] T. Montini, M. Melchionna, M. Monai, P. Fornasiero, Fundamentals and catalytic applications of CeO2-based materials, Chemical reviews 116 (10) (2016) 5987–6041.
[21] M. Panfilov,4 - Underground and pipeline hydrogen storage, In Woodhead Publishing Series in Energy, Compendium of Hydrogen Energy, Woodhead Publishing,2016,Pages 91-115.