https://rijournals.com/biological-and-applied-science/

RESEARCH INVENTION JOURNAL OF BIOLOGICAL AND APPLIED SCIENCES 3(3):25-29, 2024

©RIJBAS Publications **Online ISSN: 1115-6171**

Print ISSN: 1597-2879

Hydrogen Fuel Cells: Advancements and Applications in Clean Energy

Gakire Munyaneza H.

Faculty of Engineering Kampala International University Uganda

ABSTRACT

This review examines hydrogen fuel cell developments and uses for sustainable energy. Hydrogen fuel cells generate power from hydrogen and oxygen, releasing only water vapour. Hydrogen fuel cells' history, fundamentals, technical advances, and rising uses in transportation are covered in the article. Hydrogen fuel cells' environmental advantages and development problems are also discussed. With the global energy landscape shifting towards sustainability, hydrogen fuel cells are becoming a critical technology for decreasing greenhouse gas emissions and fostering a cleaner, more efficient energy economy.

Keywords: Hydrogen Fuel Cells, Clean Energy, Electrochemical Reaction, Renewable Energy, Transportation.

INTRODUCTION

Hydrogen fuel cells are electrochemical devices that convert chemical energy from hydrogen and oxygen into electricity through an electrochemical reaction. The process involves the movement of protons through a membrane, creating an electric current that can be used to power a wide range of applications. Fuel cells are considered one of the cleanest and most efficient ways to generate electricity, with water vapor being the only byproduct of the reaction [1]. The principles of hydrogen fuel cells date back to the 19th century when Schönbein discovered electrolysis of water. Fuel cell technology was commercialized in the late 20th century. The first fuel cell was invented by Sir William Grove in 1839. A fuel cell involves an anode, cathode, and electrolyte. Hydrogen is fed to the anode and oxygen to the cathode. This generates electricity and water vapor [2]. Fuel cell technology has matured; however, it has not yet entered the mainstream energy sector. In the last two decades, rapid advancements have been made in the areas of electrolytes, catalysts, and fuel cell designs. Fuel cell vehicles, buses, and trucks began to roll off assembly lines during the previous decade. Hydrogen power plants and hydrogen fueling stations are being built. Hydrogen is expected to play a key role in tomorrow's energy economy [3].

DEFINITION AND BASIC PRINCIPLES

Fuel cells are devices that convert chemical energy directly into electrical energy by means of electrochemical reactions, without combustion or intermediate processes involving mechanical devices (such as turbines or engines). Fuel cells are being considered for growing energy markets, including automotive applications for passenger vehicles, fuel cell buses, small portable power, and large stationary power generating plants. The focus of this review will be mainly on PEMFCs and alkaline fuel cells, the electrolytes of which are processed as membranes [4]. A fuel cell is either a rechargeable or primary battery that utilizes hydrogen as its fuel. It comprises a special type of electrolytic cell that employs both hydrogen and oxygen to generate an electric current. The hydrogen yields its electrons and thus becomes $H+$, which is an electrolyte transporting positively charged hydrogen ions. On the other side of the electrolyte, $O2$ gains electrons and, in interaction with $H+$, it produces water ($H2O$). The overall electrochemical reaction can be expressed as: $2H2 + O2 \rightarrow 2H2O$ [5]. For many years, electricity was generated by means of fuel cells in space missions, such as with Apollo or Gemini. The fuel was $H2/O2$, and the products here are water and heat. Nevertheless, for this reaction, water must be in liquid form, and the water can react with the catalyst surface, thus decreasing the effectiveness. Later on, in the 1960s, this technology was forgotten. In the late 1980s, it was reintroduced, and at the same time, phosphoric acid fuel cells were utilized in space missions [6]. Hydrogen fuel cells have attracted attention not only for the automotive industry but also for other applications such as powered bicycles, renewable energy storage, telecommunication stations, and off-grid applications [5].

ADVANCEMENTS IN HYDROGEN FUEL CELL TECHNOLOGY

Hydrogen fuel cells are often recognized as a pivotal technology contributing to global decarbonization strategies. Nevertheless, substantial gaps persist in the current scientific understanding of relevant catalytic processes, necessitating dedicated research efforts to address the present knowledge void. Ideally, the global transition to hydrogen utilization would be accompanied by an equivalent global transition to renewable hydrogen production and processing. Interestingly, meanwhile, competitive demands are arising on a variety of compositional and physical scales, calling for both radical and incremental innovations within respective global supply chains. The burgeoning need for hydrogen is tackled by innovations at all scales of demonstration, fabrication, synthesis, and analysis [7]. Following a period of major efforts to enhance cell performance, attention is turning towards methods to reduce costs through the development of less noble catalysts, the percolation of water through devices, and the design of more cost-effective bi-directional devices. Imported non-electrochemical experimental systems and pore-scale, multi-phase distribution modeling strategies are being adapted to further the performance understanding of cell performance and durability. Recent work here has documented the applicability of X-ray tomography to provide a means to track the evolution of water distribution provisions across scales and to assess the performance of bifunctional catalysts under accelerated activity cycles [8]. Progress in understanding the electrolysis system has implications for the design of polymer electrolyte membrane fuel cells (PEMFC) systems, and in a similar vein, the modeling tools to aid understanding are being parameterized to better represent fuel cell devices and their operational behavior. New PEMFC modeling tools, parameterized and validated under model conditions and repeatability, are being applied to assess the reactivity, endurance, and stability of new catalysts, iteratively informing advancements in synthesis. Understanding the structure of catalysts and their interactions and response to operational transience represents new science that can be utilized to inform improvement efforts in device lifetime and reducing reliance on platinum [9].

MATERIALS AND MANUFACTURING INNOVATIONS

Hydrogen fuel cells are electrochemical devices that convert chemical energy from hydrogen and oxygen into electricity, water, and heat, with almost zero pollutant emissions if using renewable energy. As environmental concerns and resource limitation increase, hydrogen fuel cells are emerging as an alternative to conventional systems. Significant advancements in materials and manufacturing technologies in the last decade have catalyzed the commercialization of hydrogen fuel cells [10]. Advancements in fuel cell membranes are noteworthy, particularly direct methanol fuel cell membranes, which streamline designs by combining nine components into one. Oxford University is commercializing a patented bio-inspired polybenzimidazole membrane that allows high fuel conversion efficiency at reduced costs. Manufacturing innovations include new techniques such as digital inkjet printing to improve assembly speed and reduce costs [11]. Innovations in catalysts are also significant, with researchers showing the potential of a low-cost semiconductor to transform copper into magnetite. Nobel Prize winners have discovered a new catalyst based on abundant materials instead of precious metals. Companies producing phosphorescent nanoparticles for self-powered, light-emitting plastic films could also find applications in fuel cells [12].

APPLICATIONS OF HYDROGEN FUEL CELLS

Hydrogen fuel cell technology is one of the most promising clean energy technologies that has the potential to significantly reduce greenhouse gas emissions and pollutants. The development and commercialization of hydrogen fuel cell technology depend not only on advances in technology, but also on the perception by various stakeholders of the feasibility of the hydrogen economy, which depends on economic, infrastructure, and institutional considerations. This paper addresses the current status, advancements, and potential directions for the future commercialization of hydrogen fuel cell technology, particularly for the transportation sector [13]. Hydrogen fuel cells generate electricity through a chemical reaction between hydrogen and oxygen, producing only water as a byproduct. Hydrogen can be obtained from various sources such as natural gas, electrolysis, and biomass, making it a versatile fuel. Fuel cells can operate at different temperatures and utilize hydrogen produced from different processes. Hydrogen fuel cells can potentially eliminate most pollutants and greenhouse gases produced by combustion engines if coupled with zero-emission hydrogen production (through electrolysis using renewable electricity) [14].

The development of hydrogen fuel cell technology for transportation began in the early 1990s. Since then, there have been advancements from prototypes to vehicles in commercial use. Global interest and commercialization efforts have increased since 2000, led by auto manufacturers, oil companies, and governments/universities in many countries. Fuel cell buses have been operated in North America and Europe since 2001, proving to be the first commercially viable applications. Demonstration programs in both regions are pushing for further commercialization. However, there are still technical and non-technical challenges that need to be addressed before fuel cell vehicles can be widely adopted [15].

TRANSPORTATION SECTOR

Hydrogen fuel cells are a zero-emission solution, alongside BEVs. FCEVs emit only water vapor, improving air quality. They have a higher range and faster refueling time than BEVs. They are suitable for heavy-duty vehicles and can integrate with renewable energy sources [16]. Hydrogen fuel cells can help achieve zero emissions sooner than electric vehicles in certain situations. Hydrogen fuel cell buses are already in use in some cities with renewable-powered refueling stations. However, current hydrogen production methods hinder wider use of fuel cells in transportation. Research projects are exploring large-scale hydrogen production from wind or solar energy [17]. Microalgae-based biorefinery produces low-cost hydrogen and co-products, with potential for carbon capture. Collaborations and advanced technologies are required for optimization. Large-scale projects are needed to attract investments and build the hydrogen industry [18].

ENVIRONMENTAL BENEFITS OF HYDROGEN FUEL CELLS

Hydrogen fuel cells (HFCs) use hydrogen and oxygen to generate power, producing only heat and pure water as by-products. This makes HFCs a focus for environmental engineers and scientists due to their cleanliness and green credentials. They do not contribute to global warming and can store renewable energy. Hydrogen is generated by splitting water and can be stored as a gas or liquid. The water is reused in a continuous cycle when used in fuel cells [19]. HFCs use hydrogen and oxygen to generate clean energy, with fuel cells constructed in a stack design. Hydrogen is supplied to the anode and compressed oxygen gas to the cathode. A catalyst layer splits hydrogen into protons and electrons. Electrons generate electricity while protons react with oxygen, producing heat and water [20]. Hydrogen fuel cells have received increasing interest over recent years as they have the potential to change transportation and energy consumption on the global scale. Present transportation nearly entirely relies on the use of fossil fuels, resulting in a large growth in greenhouse gas emissions over the past years, which is damaging for the global climate. Hydrogen is abundant on earth and can be produced by renewable energy processes such as electrolysis. When used in fuel cells, it produces pure water and no CO_2, which is considered one of the major pollutants causing global warming [21].

CHALLENGES AND FUTURE DIRECTIONS IN HYDROGEN FUEL CELL DEVELOPMENT

While hydrogen fuel cells offer the promise of clean, efficient energy, several hurdles inhibit progress in achieving widespread commercial use. As a nascent technology, fuel cells face a wide range of challenges, ranging from the convenience of refueling to economic viability and durability [22]. From a consumer's perspective, difficulties surrounding the commercialization of the hydrogen infrastructure revolve around the ability to find and identify fueling locations. Many people are unfamiliar with hydrogen technology and may be hesitant to switch from gasoline to hydrogen stations, particularly if they are unsure of the hydrogen fueling infrastructure. Furthermore, as fuel cell vehicles are currently more limited in range than the conventional gasoline-powered vehicles, it tends to serve as a further barrier to switching fuels [23]. Additionally, moving from hydrogen generation to gas storage and distribution offers further complexities. Currently, most hydrogen is produced from natural gas through a process termed steam methane reforming. Unfortunately, this creates extra costs since transportation of natural gas is not in place everywhere - either pipelines or cryogenic tankers must be used. Alternatively, the majority of other hydrogen production processes such as gasification or high-temperature water splitting are inadequately developed beyond the pilot plant stage with no demonstration mass production units realized [24]. Fuel cell development faces hurdles such as cost, starting, and durability. Platinum, the catalyst used, drives up the price. Efforts to reduce platinum usage are ongoing. Cold temperatures and dehydration also affect fuel cells. Degradation rates increase with higher current density [25].

Fuel cells as a leading automotive energy conversion technology are being researched at various levels. With government support, fuel cells could be used in vehicles by 2010. However, skeptics point out the lack of standardization and limited availability of hydrogen. Nonetheless, progress has been made towards fuel cell commercialization [26].

CONCLUSION

Hydrogen fuel cells represent a promising technology for achieving a sustainable energy future. With significant advancements in materials, manufacturing, and applications, hydrogen fuel cells are increasingly being recognized as a viable alternative to conventional energy sources. Their potential to reduce greenhouse gas emissions and pollutants makes them an attractive option for clean energy generation, particularly in the transportation sector. However, challenges related to cost, infrastructure, and public perception remain. Continued research, innovation, and collaboration across industries and governments are essential to overcoming these barriers and realizing the full potential of hydrogen fuel cells in the global energy transition.

REFERENCES

1. Thomas JM, Edwards PP, Dobson PJ, Owen GP. Decarbonising energy: The developing international activity in hydrogen technologies and fuel cells. Journal of Energy Chemistry. 2020 Dec 1; 51:405-15. nih.gov
2. Bossel U. Correspondence Schoenbein—Grove. Fuel Cells: From Birth to Maturity. 2024. [HTML]
3. Minutillo M, Perna A, Forcina A, Di Micco S, Jannelli E. Analyzing the levelized cost of hydrogen in refueling stations with on-site hydrogen production via water electrolysis in the Italian scenario. International Journal of Hydrogen Energy. 2021 Apr 14;46(26):13667-77. [HTML]
4. Ding Y, Cai P, Wen Z. Electrochemical neutralization energy: from concept to devices. Chemical Society Reviews. 2021. [HTML]
5. Bethoux O. Hydrogen fuel cell road vehicles: state of the art and perspectives. Energies. 2020. mdpi.com
6. Abdelkareem MA, Elsaid K, Wilberforce T, Kamil M, Sayed ET, Olabi A. Environmental aspects of fuel cells: A review. Science of The Total Environment. 2021 Jan 15;752:141803. usp.br
7. Ajanovic A, Haas R. Prospects and impediments for hydrogen and fuel cell vehicles in the transport sector. International journal of hydrogen energy. 2021. tuwien.ac.at
8. Hsu JC, Nieves LM, Betzer O, Sadan T, Noël PB, Popovtzer R, Cormode DP. Nanoparticle contrast agents for X-ray imaging applications. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology. 2020 Nov;12(6):e1642. wiley.com
9. Javaid U, Iqbal J, Mehmood A, Uppal AA. Performance improvement in polymer electrolytic membrane fuel cell based on nonlinear control strategies—A comprehensive study. Plos one. 2022. plos.org
10. Lindorfer J, Rosenfeld DC, Böhm H. Fuel cells: Energy conversion technology. Future energy. 2020. [HTML]
11. Le Phuong HA. Sustainable organic solvent nanofiltration membranes. 2022. [HTML]
12. Kaiser SK, Chen Z, Faust Akl D, Mitchell S, Pérez-Ramírez J. Single-atom catalysts across the periodic table. Chemical reviews. 2020 Oct 21;120(21):11703-809. ethz.ch
13. Halder P, Babaie M, Salek F, Haque N, Savage R, Stevanovic S, Bodisco TA, Zare A. Advancements in hydrogen production, storage, distribution and refuelling for a sustainable transport sector: Hydrogen fuel cell vehicles. International Journal of Hydrogen Energy. 2024 Jan 2;52:973-1004. sciencedirect.com
14. Fan L, Tu Z, Chan SH. Recent development of hydrogen and fuel cell technologies: A review. Energy Reports. 2021. sciencedirect.com
15. Zhao F, Mu Z, Hao H, Liu Z, He X, Victor Przesmitzki S, Ahmad Amer A. Hydrogen fuel cell vehicle development in China: An industry chain perspective. Energy Technology. 2020 Nov;8(11):2000179. wiley.com
16. Hassan Q, Azzawi IDJ, Sameen AZ, Salman HM. Hydrogen fuel cell vehicles: Opportunities and challenges. Sustainability. 2023. mdpi.com
17. Zhang W, Fang X, Sun C. The alternative path for fossil oil: electric vehicles or hydrogen fuel cell vehicles? Journal of Environmental Management. 2023. [HTML]
18. Ferreira A, Gouveia L. Microalgal biorefineries. InHandbook of microalgae-based processes and products 2020 Jan 1 (pp. 771-798). Academic Press. lneg.pt
19. Ferraren-De Cagalitan DD, Abundo ML. A review of biohydrogen production technology for application towards hydrogen fuel cells. Renewable and Sustainable Energy Reviews. 2021 Nov 1; 151:111413. [HTML]
20. Sharma S, Agarwal S, Jain A. Significance of hydrogen as economic and environmentally friendly fuel. Energies. 2021. mdpi.com
21. Singla MK, Nijhawan P, Oberoi AS. Hydrogen fuel and fuel cell technology for cleaner future: a review. Environmental Science and Pollution Research. 2021 Apr;28(13):15607-26. [HTML]
22. Miller EL, Thompson ST, Randolph K, Hulvey Z, Rustagi N, Satyapal S. US Department of Energy hydrogen and fuel cell technologies perspectives. Mrs Bulletin. 2020 Jan;45(1):57-64. synu.edu.cn

23. Scovell M, Walton A. Public beliefs about hydrogen energy technologies in Australia. 2022. researchgate.net
24. Cho HH, Strezov V, Evans TJ. Environmental impact assessment of hydrogen production via steam methane reforming based on emissions data. Energy Reports. 2022. sciencedirect.com
25. Qiao Z, Wang C, Zeng Y, Spendelow JS et al. Advanced nanocarbons for enhanced performance and durability of platinum catalysts in proton exchange membrane fuel cells. Small. 2021. wiley.com
26. Luo Y, Wu Y, Li B, Mo T, Li Y, Feng SP, Qu J, Chu PK. Development and application of fuel cells in the automobile industry. Journal of Energy Storage. 2021 Oct 1; 42:103124. google.com

CITE AS: Gakire Munyaneza H. (2024). Hydrogen Fuel Cells: Advancements and Applications in Clean Energy. RESEARCH INVENTION JOURNAL OF BIOLOGICAL AND APPLIED SCIENCES 3(3):25-29.