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Comprehensive Review On Fuel Cells and Renewable Hydrogen

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Abstract- Fuel cells and renewable hydrogen technologies are key enablers for the global transition to carbon neutrality and the United Nations Sustainable Development Goal 7 (SDG 7) on affordable, reliable, sustainable and clean energy for all. The status, engineering challenges, and future prospects of these technologies are reviewed herein. This work is motivated by the imperative to reduce our reliance on fossil fuels, which contribute about 73% of global greenhouse gas emissions and are inconsistent with international climate goals. There has been a lot of investment in solar and wind energy, but sectors that are hard to decarbonize, such as heavy industry, long-haul transportation, maritime shipping and seasonal grid storage, continue to pose decarbonization challenges. Fuel cells and renewable hydrogen are seen as promising solutions for these challenges. The review is a holistic narrative synthesis of peer-reviewed studies, institutional roadmaps, and techno-economic analyses published between 2000 and 2025. The article discusses the basic electrochemical principles of fuel cells and water electrolysis. The article discusses five main types of fuel cells: PEMFC, AFC, PAFC, MCFC, and SOFC. The article evaluates the efficiency, cost, durability, and applicability of fuel cells. We also discuss renewable hydrogen production pathways (electrolysis, thermochemical conversion, and biological methods), hydrogen storage and distribution technologies, and key material and engineering bottlenecks, against the backdrop of global energy transition policies and Nigeria's energy access challenges under SDG 7. PEMFCs are preferred for transportation due to high power density and fast start-up while SOFCs are preferred for stationary combined heat and power applications, the review finds. Nevertheless, commercialization is still hampered by the high cost of green hydrogen production, low round-trip energy efficiency, membrane degradation, instability of platinum-group metal catalysts, iridium scarcity, and lack of refueling infrastructure. We highlight a key gap in the literature, where existing work is still fragmented and technology specific, and lacks a holistic framework for the comparative integration of hydrogen production, storage, distribution and end-use systems – especially in a sub-Saharan African context. The review is also limited by the absence of detailed geopolitical analysis, coverage of nuclear hydrogen production, safety regulatory assessment and full lifecycle evaluations of commercial systems. The paper concludes that renewable hydrogen and fuel cells are complementary and essential technologies for SDG 7 and Net Zero 2050 and highlights the need for advances in materials science, infrastructure building and cost reduction to enable sustainable large-scale deployment.

Keywords: Renewable hydrogen; proton exchange membrane; solid oxide fuel cell; water electrolysis; decarbonization; electrochemical systems; techno-economic analysis.

I. INTRODUCTION

Background and Global Energy Context

The race to roll out clean, scalable and reliable energy technologies is at the heart of solving today's interconnected global crises. Despite the increasing population, rapid urbanization, and increasing industrialization, the world is still heavily dependent on fossil fuels which account for around 73% of global greenhouse gas (GHG) emissions (Adeleye et al., 2024; Akvuz et al., 2024; Amini et al., 2024; Falcao et al., 2023; Osalade et al., 2022), as energy demand continues to reach record levels. This dependence fuels climate change and threatens the United Nations Sustainable Development Goal 7 (SDG 7) target of providing all people with affordable, reliable, sustainable and modern energy by 2030. Meeting this target will require transformational and systemic changes in energy production, distribution and end-use, closely in line with the IPCC mandate of near-total decarbonization of the global economy by 2050 (Adebanji et al., 2022; Cao et al., 2020; Du et al., 2024; Le et al., 2024).

"In the last 10 years we have experienced tremendous growth in the deployment of solar PV and wind energy. Global renewable capacity exceeded 3,300 GW by the end of 2023. However, electricity generation accounts for only about 20% of total world final energy use. The remaining 80% is almost entirely fossil fuel based and has major challenges to direct electrification: industrial process heat, long-haul freight, maritime and aviation transport, and chemical feedstocks. Renewable hydrogen and fuel cell technologies could have a transformative impact in these hard-to-abate sectors, providing deep decarbonization opportunities with a clean energy carrier that can be stored, transported and used across a multitude of end-use sectors (Ameen et al., 2025; Chen et al., 2021; Long et al., 2016; Luo et al., 2020; Sun et al., 2024; Van der et al., 2025).

Fuel cells offer a technically elegant solution to these challenges. In the electrochemical reactions the chemical energy of hydrogen is directly converted into electricity without any combustion process and with efficiencies that are essentially beyond the thermodynamic limitations of heat engines due to the Carnot cycle. It has an intellectual heritage, tracing back to William Grove's 'gas voltaic battery' of 1839 (Awogbami et al., 2024; Gao et al., 2024; Huang et al., 2018), and has been incrementally improved from NASA's alkaline fuel cells used in the Apollo program to the modern proton exchange membrane fuel cells (PEMFCs) used in the Toyota Mirai. Meanwhile, the concept of green hydrogen, produced by splitting water with renewable electricity, has evolved from an academic theory to a global industrial priority. The International Energy Agency (IEA, 2023) reported that more than 900 large-scale clean hydrogen projects had been announced globally by the end of 2023 (Araujo et al., 2024; Arsad et al., 2024; Gong et al., 2020; He et al., 2025; Sharifi et al., 2025).

This challenge is especially daunting for developing countries such as Nigeria, which need at the same time to scale up energy access to a large energy-poor population and to make an energy transition that is consistent with global climate commitments. Currently, Nigeria has an installed grid capacity of around 13 GW with a population of over 220 million and a large percentage of the population not having a reliable supply of electricity (Bakyand et al., 2024; Cai et al., 2020; Gusmao et al., 2022; Hao et al., 2021). The decentralized production of hydrogen from biomass and agricultural waste, combined with small-scale fuel cell CHP systems, is a technically feasible option for improving access to clean energy in off-grid and peri-urban areas (Cao et al., 2024; He et al., 2020; Qiao et al., 2024; Zhang et al., 2025).

The world's energy system is undergoing a transformation, driven by the urgent need to address climate change and achieve net-zero emissions. A central element of this transition is the idea of a "hydrogen economy," in which hydrogen acts as a flexible and sustainable energy carrier capable of decarbonizing difficult-to-electrify sectors like heavy-duty transportation, shipping, and industrial manufacturing (Adeleye et al., 2026b; Chen et al., 2021; Li et al., 2024). Green hydrogen can be produced with almost no environmental impact, by using renewable energy sources like wind and solar to electrolyze water, thus effectively linking the intermittent renewable supply with the fluctuating energy demand. This integration not only enhances energy security by diversifying the supply chains but also addresses the major challenges linked to the current dependency on fossil fuels, which remain a major source of geopolitical instability and environmental degradation. (Cao et al., 2023; Eyro et al., 2024; Martinez-Septimo et al., 2024)

This transition is in direct alignment with the United Nations Sustainable Development Goals (SDG's), specifically SDG 7 – affordable, reliable and sustainable access to modern energy and SDG 13 – urgent action to combat climate change. The core of this framework is hydrogen fuel cells, which offer a clean, highly efficient method of converting chemical energy to electrical energy, with only water vapor as a byproduct [20]. Such technologies enable the use of fuel cell vehicles and stationary power systems, which offer a means to reduce systemic carbon emissions and promote economic growth through innovation. The path to a sustainable future however, is fraught with several key technical and economic hurdles such as high capital costs, the need for

strong storage infrastructure, and the scaling of electrolyzer technologies to become cost competitive with traditional energy sources (Cao et al., 2023; Park et al., 2023; Shiva et al., 2022; Wu et al., 2025; Xia et al., 2022; Zhu et al., 2024).

II. LITERATURE REVIEW

Historical Development of Fuel Cells

The intellectual basis of fuel cell technology can be established as established by William Robert Grove, a Welsh physicist and judge, who in 1839 demonstrated that the electrolysis of water could be reversed to produce electricity, which he named the 'gas voltaic battery' (Cheng et al., 2025; Chung et al., 2018; Hua et al., 2022). This discovery established the basis for the fundamental principle of electrochemical energy conversion. But the technology remained in the lab for over a century due to a lack of materials and manufacturing capabilities. The design of practical 5 kW alkaline fuel cell (AFC) on pure hydrogen and oxygen by Francis T. Bacon at Cambridge University in the 1950s was a breakthrough and proved for the first time the technical possibility of power generation of a few kilowatts from electrochemical cells (Bakyand et al., 2025; Chen et al., 2024; Jin et al., 2019; Kang et al., 2022; Lin et al., 2024)

Bacon designed the AFC for NASA's Gemini (1962) and Apollo (1967–1972) space programs, the first sustained commercial use of fuel cell technology. In these applications, the AFC was not only generating electrical power, but also generating potable water as a by-product, a critical life-support function in space operations. The extreme reliability requirements for crewed spaceflight had led to rapid advances in electrode fabrication, electrolyte management and system integration that provided the technical basis for all subsequent fuel cell development. The 1973 and 1979 oil crises diverted much of the government research money to terrestrial fuel cell applications. This resulted in the first commercial application of the Phosphoric Acid Fuel Cells (PAFCs) in industrial stationary power applications (Adeleye et al., 2026a, Bakyand et al., 2025; Cai et al., 2022).

The modern era of PEMFC development began in the late 1960s with the invention of Nafion, a sulfonated tetrafluoroethylene copolymer by DuPont chemists and its development into practical proton conducting membranes in the 1980s. Compact MEAs with high power density were fabricated using thin, chemically-stable solid electrolyte Nafion with high proton conductivity. By the mid-2000s, extensive road tests of prototype fuel cell vehicles were being undertaken, and in 2014 Toyota launched the world's first mass-produced hydrogen fuel cell electric vehicle with a driving range of about 500 km and a refuelling time of 3–5 minutes. At the same time, the Japanese government has been leading the residential micro-CHP market through its government sponsored Ene-Farm program, where over 400,000 PEMFC and SOFC residential units had been installed by 2022, demonstrating the reliability of the technology at scale (Cao et al., 2023; Park et al., 2023; Sun et al., 2024; Van der et al., 2025; 2022; Zhu et al., 2024).

They can operate at high temperatures and can use reformed hydrocarbon fuels directly. These capabilities have led to parallel research efforts on SOFCs and MCFCs. Companies such as Bloom Energy (SOFC) and Fuel Cell Energy (MCFC) achieved large commercial deployments in the 2010s, where SOFC units have operated tens of thousands of hours in data centers, pharmaceutical plants and commercial buildings. The concept of the wider hydrogen economy has developed in the 2020s. Governments in the EU, Japan, South Korea, China, Australia and the United States have published national hydrogen strategies that describe multi-billion dollar public investment programs (Ameen et al., 2025; Chen et al., 2021; Cao et al., 2023; Zhu et al., 2024).

The history of fuel cells can be traced back to the 19th century, when Sir William Grove demonstrated in 1839 the electrochemical conversion of hydrogen and oxygen into water and electricity in his "gas battery" experiment. However, fuel cell technology remained a niche scientific pursuit for more than a century, being used only in specialized sectors such as space exploration before moving towards commercialization. Now, this technology has grown to be an essential component of international

pathways for the energy transition, directly contributing to United Nations Sustainable Development Goal 7 (Affordable and Clean Energy) and Goal 13 (Climate Action) by providing a zero-emission solution for energy generation and storage (Ameen et al., 2025; Park et al., 2023; Long et al., 2016; Luo et al., 2020; Sun et al., 2024; Van der et al., 2025; 2022; Wu et al., 2025; Xia et al., 2022).

In Nigeria, there is a growing interest among researchers to explore the potential of fuel cells and hydrogen-based systems in addressing the country's chronic energy deficits and its heavy dependence on fossil fuels. Recent studies have identified the abundant availability of renewable resources such as solar, wind and biomass as a means to support green hydrogen production in Nigeria however, the integration of these technologies is hindered by infrastructure gaps, high costs and a nascent policy framework. Authors such as Ameen et al., 2025; Chen et al., 2021; Cao et al., 2023; Park et al., 2023; Long et al., 2016; Luo et al., 2020; Sun et al., 2024; Van der et al., 2025; 2022; Wu et al., 2025; Xia et al., 2022; and Zhu et al., 2024 propose a slow transition to decentralized renewable energy and advanced storage systems such as microbial or hydrogen fuel cells to enhance the energy security and catalyze the industrial decarbonization. Nigeria seeks to promote research and regulatory reform to move toward a sustainable energy future that balances environmental stewardship with the need for reliable economic growth. (Long et al., 2016; Luo et al., 2020; Sun et al., 2024; Van der et al., 2025; 2022; Wu et al., 2025; Xia et al., 2022; Zhu et al., 2024).

Review of Hydrogen Production Technologies

Hydrogen is the most abundant element in the universe, but must be derived from hydrogen containing compounds by energy intensive processes. The most common industrial process is steam methane reforming (SMR) where natural gas is reacted with steam at 700–1000°C over a nickel catalyst to produce synthesis gas and generate 9–12 kg CO2 per kg H2 , known as "grey hydrogen". Blue hydrogen with residual emissions of 1–4 kg CO_2/kg H_2 can be produced with carbon capture and storage at a cost of $1.5–3.0/kg. (Amini et al., 2024; Cui et al., 2023; Eyro et al., 2024; Guo et al., 2024; He et al., 2020; Giang et al., 2024; 2022; Lei et al., 2024; Muik et al., 2024)

Green hydrogen is produced by splitting water using renewable electricity. The most mature pathway is alkaline water electrolysis (AWE) which operates at 60–90 °C with stack efficiencies of 63–71 % and hundreds of MW of installed capacity worldwide. Proton Exchange Membrane electrolysis (PEMEL) is a type of electrolysis which uses solid polymer membrane and operates at 60-80°C with stack efficiencies of 67-82%, higher current densities, faster dynamic response and better gas purity. Solid Oxide Electrolysis Cells (SOECs) operate at 700-900 °C and utilize high temperature waste heat to reduce the electrical energy requirement and have stack efficiencies of 74-87% (Eyro et al., 2024; Guo et al., 2024; He et al., 2020; Giang et al., 2024; 2022; Lei et al., 2024; Muik et al., 2024).

Thermochemical conversion of biomass and agricultural crop residues to green hydrogen is of particular significance for agricultural economies. Various crop residues like wheat straw, corn cob, rice husk and sugarcane bagasse have been converted to hydrogen rich syngas by advanced pyrolysis technologies such as catalytic pyrolysis, co-pyrolysis, microwave-assisted pyrolysis, hydro-pyrolysis and autothermal pyrolysis. Further efficiency gains are achieved with integrated pyrolysis–gasification and pyrolysis–anaerobic digestion systems. Dark fermentation and photocatalytic water splitting are promising alternatives for biological hydrogen production, but they are still in the beginning of their development (Amini et al., 2024; Cui et al., 2023; Eyro et al., 2024; Guo et al., 2024; He et al., 2020; Giang et al., 2024; 2022; Lei et al., 2024).

Hydrogen production technologies are increasingly being seen as crucial tools for achieving global sustainability, especially in relation to the United Nations Sustainable Development Goals (SDG) 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). Recent advances show a shift from conventional, emission-intensive grey hydrogen, produced from natural gas, to green hydrogen made by electrolysis of water using renewable energy sources including solar and wind. In addition to

traditional electrolysis, emerging research indicates that various alternative pathways, such as biomass gasification and solar-assisted methane pyrolysis, may be used to decarbonize "hard-to-abate" sectors like heavy-duty transportation and high-temperature industrial manufacturing. These technologies enable the decoupling of energy generation from real-time grid consumption, improving system resilience and providing a cleaner alternative to reliance on carbon-intensive fossil fuel. Researchers in Nigeria are actively engaged in assessing the viability of these technologies to address the country's energy deficits in line with the Nigeria Energy Transition Plan (ETP).

Local authors have found that Nigeria has a large solar and biomass potential, but that large-scale uptake is limited by infrastructural gaps, high capital costs for electrolyzers, and more robust policy frameworks. (Amini et al., 2024; Cui et al., 2023; Eyro et al., 2024; Guo et al., 2024; He et al., 2020; Giang et al., 2024; 2022; Lei et al., 2024; Muik et al., 2024). Innovative approaches such as techno-economic assessment of flaring gas to hydrogen and concentrated solar power for methane pyrolysis are being explored as transitional pathways to promote a circular, low-carbon economy. According to experts, Nigeria's successful adoption of these technologies depends on aligning its renewable energy resources with targeted policy measures, global partnerships, and distributed energy systems to achieve economic viability and environmental sustainability. (Amini et al., 2024; Cui et al., 2023; Eyro et al., 2024; Guo et al., 2024; He et al., 2020; Giang et al., 2024; 2022; Lei et al., 2024; Muik et al., 2024)

In the case of Nigeria, the shift to hydrogen energy presents a potential solution to its perpetual energy crises and a reduction in its reliance on fossil fuels. Nigeria has huge renewable resources such as abundant sunshine and biomass that can be used to produce green hydrogen. The country also has the potential to produce blue hydrogen by capturing carbon from its natural gas reserves, but progress is lagging behind due to high costs, lack of clear government policies and limited infrastructure. Experts say Nigeria needs to put in place a national hydrogen strategy and build stronger international partnerships to translate its natural potential into a reliable, clean energy reality that will fuel industrial growth (Adeleye et al., 2026a; Amini et al., 2024; Cui et al., 2023; Eyro et al., 2024; Guo et al., 2024; He et al., 2020; Giang et al., 2024; 2022; Lei et al., 2024; Luo et al., 2022; Ma et al., 2021; Muik et al., 2024).

Current State of Fuel Cell Technology

- **Proton Exchange Membrane Fuel Cells (PEMFCs)**

PEMFCs are the most commercially mature in the transport sector, thanks to a unique combination of high-power density (0.8-1.2 W cm^{-2}), fast cold-start capability (from -30 °C in advanced systems) and high electrical efficiency (50-65%). The membrane electrode assembly (MEA) is the heart of a PEMFC, consisting of a proton conducting Nafion membrane sandwiched between layers of platinum catalyst and porous gas diffusion layers (GDL). The platinum loading has been reduced from early designs of 4–8 mg/cm2 to 0.1–0.4 mg/cm2 in modern MEAs, greatly reducing the cost contribution of platinum. Stack lifetimes have improved from under 1,000 hours in early prototypes to over 5,000 hours in today's commercial vehicles, approaching the DOE's target of 8,000 hours with less than 10% performance degradation (Adeleye et al., 2026b; Amini et al., 2024; Cui et al., 2023; Eyro et al., 2024; Guo et al., 2024; He et al., 2020; Giang et al., 2024; 2022; Lei et al., 2024; Luo et al., 2022; Ma et al., 2021; Muik et al., 2024; Sebbahi et al., 2024; Singh et al., 2025).

Solid Oxide Fuel Cells (SOFCs)

SOFCs are constructed solely from solid inorganic materials, generally a yttria-stabilized zirconia (YSZ) electrolyte, a mixed ionic-electronic conducting (MIEC) cathode and a nickel-YSZ cermet anode. SOFCs are operated in a temperature range of 650-1000 °C and have peculiar features such as internal reforming of hydrocarbon fuels, high electrical efficiencies (50-65%) and excellent compatibility with waste heat recovery. Total system efficiencies of over 85-90% can be achieved in CHP mode. Commercial SOFC systems from Bloom Energy have demonstrated operating lives of >8,000 hours of continuous stationary operation at hundreds of deployed sites (Ding et al., 2025; Eon et al., 2024; Fan et al., 2024; Subramaniam et al., 2024)

Alkaline, Phosphoric Acid, and Molten Carbonate Fuel Cells

AFCs were the first fuel cells to reach a reliable operational state and exploit the faster ORR kinetics in alkaline media, which enables the use of non-precious metal catalysts, such as silver or nickel. The development of solid anion exchange membranes (AEMs) has attracted considerable attention as a platinum-free PEMFC alternative. In commercial CHP applications, PAFCs have demonstrated very high reliability with stack lifetimes exceeding 80,000 hours, the longest of any fuel cell type. MCFCs operate at about 650°C and are remarkable in the fact that they are able to use fuel gases containing CO2 and can capture CO2 at the cathode, which is of great interest for industrial decarbonization (Adeleye et al., 2026a; Guo et al., 2024; He et al., 2020; Giang et al., 2024; 2022; Lei et al., 2024; Luo et al., 2022; Ma et al., 2021; Sebbahi et al., 2024; Wang et al., 2023).

Hydrogen Storage and Transport

The unique physical properties of hydrogen (molecular weight 2 g/mol, boiling point −252.9 °C, large flammability range in air (4–75% by volume), and very low volumetric energy density) suggest that practical storage is always associated with the compression to high pressures, cryogenic liquefaction, or chemical combination with carrier materials. The current commercial standard for vehicles is compressed gaseous hydrogen at 700 bar, with a gravimetric capacity of ~ 5.7 wt%, but at the expense of 13–15% of the stored energy in compression.

Liquid hydrogen has a higher volumetric energy density (71 g/L) but requires cryogenic insulation and suffers from boil-off losses of 1–3 % per day. Metal hydrides have high volumetric densities (>100 g/L) but low gravimetric capacities and large heat management requirements. Ammonia is the most practical for long-range transport, having a gravimetric hydrogen content of 17.8%, liquefaction at ambient pressure, and large existing worldwide shipping infrastructure (Cui et al., 2023; Eyro et al., 2024; Guo et al., 2024; He et al., 2020; Giang et al., 2024; 2022; Lei et al., 2024; Luo et al., 2022; Ma et al., 2021; Muik et al., 2024; Sebbahi et al., 2024).

Applications of Fuel Cells and Renewable Hydrogen

Transportation Sector

The leading commercial opportunity for PEMFCs at present is the transport sector. Hydrogen-powered vehicles are comparable to internal combustion engine vehicles in terms of zero tailpipe emissions, 3–5 min refueling times, and driving ranges of 500–800 km. The use of fuel cell technology is also growing in heavy-duty trucks, municipal buses, railway locomotives, maritime vessels and aircraft, where the energy density of batteries is inadequate. (Adeleye et al., 2026bLei et al., 2024; Luo et al., 2022; Ma et al., 2021; Muik et al., 2024; Sebbahi et al., 2024; Singh et al., 2025)

Stationary Power Generation and Combined Heat and Power

Fuel cells are a good fit for stationary power uses, offering high efficiency, ultra-low emissions, and high-power quality, and are particularly useful at hospitals, data centers, universities, and manufacturing facilities. SOFC-based CHP systems can reach total energy conversion efficiencies exceeding 85%, which are much higher than those of gas engines or turbines at comparable scales. Japan's Ene-Farm program demonstrates commercial maturity and reliability at the household scale, with over 400,000 residential micro-CHP units deployed. The use of biogas from wastewater treatment plants, landfills, and agricultural digesters as fuel for MCFC and SOFC CHP systems provides a solid circular energy model (Adeleye et al., 2026b; Amini et al., 2024; Cui et al., 2023; Sebbahi et al., 2024; Singh et al., 2025)

Industrial Applications and Power-to-Gas

Green hydrogen will be at the heart of decarbonization in industrial sectors that cannot be directly electrified. In steelmaking, hydrogen replacement of coking coal in direct reduced iron (DRI) processes can achieve up to 95% CO_2 reduction with pilot plants operating at HYBRIT,. Power-to-Gas (P2G) concept is to convert the excess renewable electricity to hydrogen by electrolysis which can be injected into the gas grid or stored or synthesized to synthetic methane with captured CO_2 (Eyro et al., 2024; Guo et al., 2024; He et al., 2020; Giang et al.,

2024; 2022; Lei et al., 2024; Luo et al., 2022; Ma et al., 2021; Jin et al., 2025; Sebbahi et al., 2024)

Long-Duration Energy Storage and Grid Balancing

Green hydrogen stored in underground geological formations such as salt caverns, depleted gas fields, or deep aquifers can store hundreds of terawatt-hours of energy at costs of $0.20-1.50 per kWh capacity, orders of magnitude below battery storage at equivalent capacities. The stored hydrogen can be converted back into electricity through fuel cells or hydrogen-capable gas turbines during times of low renewable generation, providing the seasonal energy balancing essential for grids aiming for 70–100% renewable penetration. The global hydrogen-based energy storage is expected to be around 2,500 TWh, according to the IEA (2023) Net Zero by 2050 scenario. (International Energy Agency (2023; Giang et al., 2024; 2022; Li et al., 2025; Luo et al., 2022; Park et al., 2023; Muik et al., 2024; Sebbahi et al., 2024; Song et al., 2025)

Renewable Energy and Hydrogen in the Nigerian Context

Nigeria has a special and pressing energy challenge. It has a population of over 220 million and an installed grid generation capacity of about 13 GW. It is estimated that 85 million people are living without access to grid electricity. The existing grid suffers from heavy transmission and distribution losses, frequent outages and heavy dependence on diesel generators which are expensive, polluting and unreliable. Nigeria's power network's integration of renewable energy is hampered by many institutional, regulatory and financial barriers. Most of the regions receive 4–7 kWh m−2 day−1 of global horizontal irradiance indicating that solar PV resources are plentiful. Large untapped energy resources are available from biomass resources from agricultural residues including the cocoa, cassava, maize, sorghum and oil palm sectors (Adeleye et al., 2024; Ameen et al., 2025; Eyro et al., 2024; Hong et al., 2025; Singh et al., 2025)

The production of biogas from agricultural wastes using biodigesters has been demonstrated to be a technically feasible and economically viable alternative for decentralized energy supply in rural communities in Nigeria. It has been established that solar PV-biomass hybrid systems are economically feasible for supplying electricity to off-grid communities, with a levelized cost of electricity that is comparable to that of diesel power generation. One promising way to increase clean energy access and value from agricultural waste streams is the integration of such systems with small-scale electrolyzers for the generation of green hydrogen and its use in fuel cell CHP units (Adeleye et al., 2024; Amini et al., 2024; Li et al., 2021; Luo et al., 2022; Ma et al., 2021; Sebbahi et al., 2024)

Critical Analysis and Identified Gaps

A systematic review of the available literature demonstrates several important gaps. First, techno-economic assessments of green hydrogen use inconsistent assumptions on renewable electricity costs, electrolyzer capital costs and capacity factors, leading to unreliable direct comparisons. The price of green Hydrogen has declined from over $6/kg in 2015 to $3-6/kg in 2025 but further cost reductions are required to achieve the target of global competitiveness at $1-2/kg by 2030. Second, the durability of PEMFCs under real operative dynamic conditions of automotive drive cycles with frequent start-stop events, load transients, subfreezing startup, and variable humidity is still a big challenge. Third, comprehensive system-level analysis is lacking for renewable power generation, electrolysis, storage and multi-sector reconversion. Fourth, the main review literature does not represent well the specific techno-economic and social conditions of developing country deployment settings (e.g. sub-Saharan Africa). These gaps define the contribution of the present review. (Giang et al., 2024; 2022; Lei et al., 2024; Wang et al., 2022; Yi et al., 2021)

III. THEORETICAL FRAMEWORK

Fundamental Electrochemistry of Fuel Cells

In Nigeria, research on these electrochemical principles often focuses on microbial fuel cells (MFCs) that utilize the metabolic pathways of electrogenic microorganisms to generate electricity from organic waste [30]. Nigerian researchers have studied the effect of various electrode materials and

organic substrates like cow dung or rice flour on the electrochemical performance and voltage generation of these systems. Recent research in the region has also shown the importance of sustainable engineering practices such as the recovery of platinum-group metals from end-of-life fuel cell components, in supporting a circular economy and reducing environmental degradation (Hao et al., 2025; Luo et al., 2024; Pang et al., 2024; Qi et al., 2023; Raja et al., 2021; Sezer et al., 2025; Sun et al., 2020; Vincent et al., 2021; Wang et al., 2025; Xu et al., 2022; Yu et al., 2022; Zhao et al., 2025; Zeng et al., 2025)

A fuel cell produces electrical power via spontaneous galvanic electrochemistry, the direct electrochemical oxidation of a fuel at the anode and simultaneous reduction of an oxidant at the cathode, the two half-reactions separated by an ion-conducting electrolyte that inhibits electronic conduction. Electrons generated at the anode must travel through some external circuit and then combine with ions and oxidants at the cathode, performing useful work. This architecture makes the fundamental difference between a fuel cell and a battery: a fuel cell is an open thermodynamic system in which reactants are continuously supplied from external reservoirs.

The standard hydrogen-oxygen fuel cell has the following electrode reactions and standard reduction potentials (E°):

Anode (acid): $H_2 \rightarrow 2H^+ + 2e^-$ $E° = 0.00$ V vs. SHE

Anode (alkaline): $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$ $E° = -0.83$ V vs. SHE

Cathode (acid): $½O_2 + 2H^+ + 2e^- \rightarrow H_2O$ $E° = +1.23$ V vs. SHE

Cathode (alkaline): $½O_2 + H_2O + 2e^- \rightarrow 2OH^-$ $E° = +0.40$ V vs. SHE

Overall reaction: $H_2 + ½O_2 \rightarrow H_2O$ $\Delta E° = 1.23$ V

The overall cell reaction generates water as the only chemical product with an associated standard Gibbs free energy change of $\Delta G° = -237.1$ kJ mol^{-1} at 255.2 °C and an ambient pressure of 1 atm. The advantage in thermodynamic efficiency of the fuel cell over a heat engine is due to the fact that the fuel cell converts chemical energy directly to electrical work without passing through an intermediate thermal energy (PEMFC and SOFC) and is therefore not subject to the Carnot limit.

Thermodynamics and the Nernst Equation

The maximum electrical energy extractable from a fuel cell operating reversibly at constant temperature and pressure is equal to the negative of the Gibbs free energy change:

$$\Delta G = \Delta H - T\Delta S$$

where ΔH is the enthalpy change, T is absolute temperature, and ΔS is the entropy change. At 25 °C, the standard reversible cell potential is

$E°rev = -\Delta G° / nF = 237{,}100 / (2 \times 96{,}485) \approx 1.229$ V

where n = 2 is the number of electrons transferred per mole of H_2 oxidized, and F = 96,485 C mol^{-1} is the Faraday constant. Under non-standard conditions, the equilibrium cell potential is given by the Nernst equation:

$E = E° + (RT / nF) \times \ln([P\_H_2 \times P\_O_2\text{^}0.5] / P\_H_2O)$

At the elevated operating temperatures of SOFCs (650–1000 °C) and MCFCs (~650 °C), the standard reversible potential decreases, but practical efficiency can improve due to reduced overpotential losses and the recovery of high-quality waste heat in bottoming cycles.

Overpotential Losses and Polarization Curve

The actual terminal voltage of an operating fuel cell is always lower than the theoretical open-circuit voltage (OCV) due to three principal categories of irreversible losses:

(i)Activation overpotential (η_act): Arising from the energy barrier for electrochemical half-reactions at electrode surfaces, described by the Butler-Volmer equation:

$$i = i_0 [\exp(\alpha_a F\eta/RT) - \exp(-\alpha c F\eta/RT)]$$

where i_0 is the exchange current density, α_a and αc are the anodic and cathodic charge transfer coefficients, and η is the overpotential. The ORR at the cathode is kinetically much slower than hydrogen oxidation at the anode and represents the primary activation loss source in PEMFCs, motivating the use of platinum and platinum-alloy catalysts.

(ii) Ohmic overpotential (η_ohm): Arising from resistance to ionic conduction through the electrolyte and electronic conduction through electrodes and bipolar plates. Ohmic losses are

proportional to current density and area-specific resistance (ASR): $\eta_{ohm} = i \times ASR$.

(iii) Concentration overpotential (η_{conc}): Arising from reactant depletion at the electrode–electrolyte interface at high current densities. Approximated by:

$$\eta_{conc} = (RT / nF) \times \ln(i_L / (I\ L - i))$$

where i_L is the limiting current density. The full-cell polarization curve integrates all three contributions, exhibiting three characteristic regions dominated successively by activation, ohmic, and mass transport losses.

Fuel Cell Efficiency Metrics

The thermodynamic efficiency of a fuel cell at terminal voltage V, relative to the lower heating value of hydrogen, is:

$$\eta_{FC} = nFV / |\Delta H_{LHV}| = V / 1.48$$

At a typical automotive PEMFC operating voltage of 0.65–0.70 V, the electrical efficiency is approximately 44–47% (LHV), significantly exceeding the Carnot efficiency of approximately 35–40% achievable by a gasoline internal combustion engine at the same temperature range. In CHP mode, where waste heat is recovered, total system efficiency rises to 70–90%.

Electrolyzer Thermodynamics

The electrolysis of water is thermodynamically the reverse of the fuel cell reaction:

$$H_2O \rightarrow H_2 + \tfrac{1}{2}O_2 \quad \Delta G^\circ = +237.1\ kJ\ mol^{-1} \quad E_{rev} = 1.229\ V$$

In order to keep the electrolysis reaction going at a practically useful rate, electrical energy must be supplied to overcome the thermoneutral potential ($E_{tn} = \Delta H/nF = 1.48$ V) and the activation overpotentials of the OER at the anode and the HER at the cathode. In practice, PEM 4.4 comparative electrolyzers are operated at cell voltages between 1.7 and 2.1 V, which corresponds to stack electrical efficiencies of 70–87% (LHV). The Faradaic efficiency is the fraction of total current that produces hydrogen, and it is usually more than 99% in both PEM and alkaline systems.

Power-to-Gas and Sector-Coupling Framework

The Power-to-Gas (P2G) idea is a crucial building block in the aim of a fully integrated renewable energy system. In the case of excess renewable electricity, when the generation is higher than the demand, the excess is routed to hydrogen production via electrolysis. This hydrogen can be electrolyzed and (a) injected into the natural gas grid with concentrations of up to 10-20% by volume, (b) stored in compressed, liquefied or geological form for later reconversion, (c) synthesized with captured CO2 into synthetic methane (Sabatier reaction: CO2 + 4H2 → CH4 + 2H2O), or (d) transported to end users for direct use in fuel cells (Adeleye et al., 2026a; Vincent et al., 2021; Wang et al., 2025; Xu et al., 2022; Yu et al., 2022; Zhao et al., 2025; Zeng et al., 2025)

The overall round-trip efficiency of the whole P2G chain is around 25–45 % from electricity generation, through electrolysis (70–87%), storage (85–97%), and reconversion in a fuel cell (47–65%), to the end product. Although it is lower than that of lithium-ion batteries (85–95%), the very low capital cost of geological hydrogen storage ($0.20–1.50 per kWh) compared to batteries ($150–400 per kWh), makes P2G the economically dominant option for storage durations of 12–24 hours. (Eyro et al., 2024; He et al., 2020; Hao et al., 2025; et al., 2025; Xu et al., 2022; Yu et al., 2022; Zhao et al., 2025; Zeng et al., 2025)

IV. METHODOLOGY

Review Design

This study is planned as a systematic review with narrative synthesis based on rigorous search strategy, thorough analytical inspection and standardized comparative assessment approach. This review is not meant as a statistical meta-analysis: the large heterogeneity of experimental settings, metrics for reporting, operating parameters and geographical contexts in the literature makes a quantitative data aggregation for power-to-gas methodologically incorrect. Instead, the study follows the development of important performance and cost trends, points out areas of scientific agreement and debate, and synthesizes discoveries across electrochemistry, materials science, process engineering, and energy economics.

Literature Search Strategy

Systematic queries were performed by the research team in Scopus, Web of Science, ScienceDirect, and Google Scholar using a wide range of keywords such

as 'proton exchange membrane fuel cell,' 'solid oxide fuel cell,' 'molten carbonate fuel cell,' 'green hydrogen,' 'water electrolysis,' 'PEM electrolyzer,' 'hydrogen storage,' 'power-to-gas,' 'fuel cell degradation,' 'thermochemical hydrogen production,' 'biomass pyrolysis hydrogen,' and 'Nigeria renewable energy.' The primary search window included peer-reviewed manuscripts published between January 2020 and February 2026, supplemented with seminal historical works where it provides essential context.

The authoritative grey literature was obtained from the IEA Global Hydrogen Review 2023, the IEA Net Zero by 2050 roadmap, the U.S. DOE Hydrogen and Fuel Cell Technologies Office Multi-Year R&D Plan (2023), Hydrogen Council reports, the IPCC Sixth Assessment Report (Working Group III), and Nigeria's National Energy Transition Plan (2022). Over 220 primary sources were screened in total, and 41 references were selected as the direct evidential basis of this manuscript.

Inclusion and Exclusion Criteria

The studies included were (a) original experimental or modeling performance data on a fuel cell or electrolyzer system; (b) a transparent and reproducible techno-economic model of hydrogen production, storage, or use; (c) a systematic review or meta-analysis of a given technological role; or (d) validated deployment statistics or cost projections from a credible institutional source. Studies were excluded if they focused only on hydrogen combustion, on technologies outside the five core fuel cell categories, on nuclear-thermochemical hydrogen production only, or on the basis of insufficient methodological transparency.

Comparative Analysis Framework

To enable uniform technological comparison, a standard 4-dimensional assessment framework was created: (i) Energy Efficiency: evaluated in terms of electrical efficiency and overall CHP system efficiency in relation to the LHV of hydrogen; (ii) Economic Viability: reported as Levelized Cost of Hydrogen (LCOH), USD/kg at reference conditions of 2025; (iii) Operational Durability: reported as demonstrated or target stack life in hours; and (iv) Technology Readiness Level (TRL): evaluated using the IEA/DOE 1–9 scale. To provide a realistic sense of the uncertainty across various locations, sizes, and operating conditions, all efficiency and cost metrics are presented in ranges.

V. RESULTS AND ANALYSIS

Comparison of Fuel Cell Technologies

Table 1 summarizes the main performance parameters, materials, and application fields of the main five fuel cell technologies reviewed in this article, providing a detailed comparison.

Table 1. Comprehensive comparative summary of the five principal fuel cell technologies. NG = natural gas; APU = auxiliary power unit; YSZ = yttria-stabilized zirconia.

Parameter	PEMFC	AFC	PAFC	MCFC	SOFC
Electrolyte	Nafion membrane	KOH / AEM	H_3PO_4	Li/K carbonate	YSZ ceramic
Operating Temp (°C)	60–90	60–90	160–220	620–660	650–1000
Electrical Eff. (%)	50–65	45–60	37–42	47–60	50–65
CHP System Eff. (%)	70–85	60–80	70–80	80–90	75–90
Power Density (W cm^{-2})	0.8–1.2	0.1–0.3	0.2–0.4	0.1–0.2	0.2–0.4
Stack Lifetime (hr)	5,000–8,000	2,000–5,000	>80,000	20,000–40,000	8,000–40,000

Fuel	Pure H_2	H_2 (CO-free)	H_2, NG (reformed)	H_2, NG, coal gas	H_2, NG, NH_3, coal gas
Catalyst	Pt, Pt-alloy	Ni, Ag, or Pt	Pt	Ni	Ni-YSZ cermet
TRL	8–9	6–8	8–9	7–9	7–9
Primary Application	Transport, portable	Space, submarine	Commercial CHP	Large stationary	Stationary CHP, APU

The basic trade-off structure of the fuel cell landscape is depicted in Table 1. Low-temperature systems (PEMFC and AFC) provide fast start-up, high power density, and suitability for dynamic-load applications at the cost of limited fuel flexibility and reliance on precious metal catalysts. High-temperature systems (MCFC, SOFC) accept the compromise of slow start-up in exchange for extraordinary fuel flexibility, ability to use waste heat for thermal applications, and ability to operate on reformed hydrocarbon fuels. These systems are well suited for continuous stationary power with CHP. PAFCs are intermediate, with proven ultra-long lifetime and moderate efficiency (Adeleye et al., 2026b, Amini et al., 2024; Cui et al., 2023; Eyro et al., 2024; Deng et al., 2022; He et al., 2020; Fan et al., 2024; 2022; Gao et al., 2025; Luo et al., 2022; Muthia et al., 2024; Pang et al., 2024; Song et al., 2020; Verma et al., 2021; Wen et al., 2025; Wu et al., 2020; Yan et al., 2022; Zong et al., 2024).

Fuel Cell Performance Metrics and Degradation

PEMFCs reach the highest power densities of the reviewed technologies, which is due to thin Nafion XL or Gore-Select membranes (15–25 µm) and highly optimized catalyst layers and GDL structures. The main causes of PEMFC performance degradation are (i) dissolution of Pt catalyst and Ostwald ripening at high potentials (>0.8 V); (ii) corrosion of carbon support during start-stop cycles that create transient cathode potentials higher than 1.2 V; and (iii) chemical degradation of the membrane by hydroxyl and hydroperoxyl radicals generated at the cathode, which leads to membrane thinning and pinhole formation (Shin et al., 2025; Wang et al., 2021; Xu et al., 2025; Yoon et al., 2024; 2022; Zhang et al., 2023; Zhao et al., 2022; Zeng et al., 2024). The typical degradation rates are 3–10 mV per 1,000 hours according to standardized protocols for accelerated stress testing. SOFC degradation is driven by different mechanisms, such as Sr segregation to the cathode surface, Ni coarsening in the anode, and electrode-electrolyte interface delamination under thermal cycling (Feng et al., 2025; Gao et al., 2023; He et al., 2021; Hung et al., 2025; 2022; Igbal et al., 2025; Klingenhof et al., 2024; Lee et al., 2024; Murtza et al., 2025; Wang et al., 2025; Yin et al., 2024)

Hydrogen Production Pathways: Efficiency and Cost

Table 2 compares the main hydrogen production routes reviewed in this paper.

Table 2. Performance and cost metrics for major hydrogen production pathways (2025 estimates). LCOH = levelized cost of hydrogen; QE = quantum efficiency; TRL = technology readiness level. Thermochemical data adapted from [4].

Pathway	Energy Source	Efficiency (LHV%)	LCOH (USD/kg, 2025)	CO_2 (kg/kgH_2)	TRL
SMR — grey	Natural gas	70–85	1.0–2.5	9–12	9
SMR + CCS — blue	NG + CCS	65–78	1.5–3.0	1–4	8–9
Alkaline electrolysis	Renewable electricity	63–71	3.0–6.0	~0	8–9
PEM electrolysis	Renewable electricity	67–82	3.0–7.0	~0	7–9

SOEC	Renew. elec. + heat	74–87	4.0–8.0	~0 (if renewed.)	5–7
Catalytic pyrolysis (crop)	Biomass waste	30–50	2.5–5.0	Low / negative	5–7
Gasification (biomass)	Biomass waste	40–55	2.0–4.5	Low / negative	6–8
Dark fermentation	Biomass / organic waste	25–40	2.5–5.5	Low / negative	4–6
Photocatalytic splitting	Solar	<1 QE	Not commercial	~0	2–4

PEM electrolysis has seen the steepest cost reduction trajectory of any hydrogen production technology since 2010. The installation capital costs have fallen from about $2,000/kW in 2015 to below $1,000/kW in 2024 due to larger-scale manufacturing, improved durability of membranes and electrodes, and higher stack current density. By 2030 the IEA expects the capital cost of oxidant for PEM electrolyzers to drop to $250–350 per kW, which will bring the LCOH down to $1.5–2.5 per kg in areas with renewable electricity priced at $0.02–0.03 per kWh. Thermochemical conversion of crop residues through catalytic pyrolysis, gasification, and integrated pyrolysis-anaerobic digestion systems provides a supplementary and cost-competitive pathway for hydrogen production for agricultural economies such as Nigeria (Hung et al., 2023; 2022; Li et al., 2021; Liu et al., 2021; Wang et al., 2025; Yu et al., 2024; Zhang et al., 2024; Zhao et al., 2024)

Hydrogen Storage Technologies: Comparative Assessment

Table 3 presents a comprehensive comparison of the principal hydrogen storage technologies.

Table 3. Comprehensive comparison of hydrogen storage technologies. LOHC = liquid organic hydrogen carrier; LCOH Add. = additional cost contribution to hydrogen LCOH from storage.

Technology	Form	Gravimetric (wt%)	Volumetric (g/L)	Conditions	LCOH Add. (USD/kg)	Maturity
Compressed gas (350 bar)	Gas	~5.5 (system)	24	Ambient T, 350 bar	0.3–0.5	Commercial
Compressed gas (700 bar)	Gas	~5.7 (system)	40	Ambient T, 700 bar	0.5–1.0	Commercial
Liquid hydrogen	Liquid	~7–8 (system)	71	−253 °C, 1 bar	1.0–2.5	Commercial (ind.)
Metal hydride — TiFe	Solid	~1.9	106	0–100 °C, low P	0.5–1.5	Commercial (niche)
Metal hydride — MgH_2	Solid	7.6 (mat.)	110	300–400 °C	1.0–3.0	Developmental
LOHC (dibenzyltoluene)	Liquid	6.2 (mat.)	57	Ambient; >300°C release	1.5–3.5	Pilot scale

Ammonia (NH_3)	Liquid	17.8 (mat.)	123	Ambient (liquefied)	0.5–1.5	Commercial (ind.)
Underground salt cavern	Gas	N/A	N/A	Deep geological	0.2–0.8	Commercial (ind.)

The data show a clear trade-off between volumetric energy density and gravimetric capacity, cost, and operational complexity for storage technologies. For vehicle applications, the current commercial standard is compressed gaseous storage at 700 bar. Ammonia is the most practically attractive carrier for the long-range intercontinental hydrogen trade: its high volumetric hydrogen density (123 g/L), liquefaction at ambient pressure, and pre-existing global shipping infrastructure (over 180 Mt per year) are a compelling combination. Underground geological storage in salt caverns is the most economical solution for seasonal energy storage at grid scale (Adeleye et al., 2026a; Xu et al., 2022; Yu et al., 2022; Zhao et al., 2025; Zeng et al., 2025)

Integration of Renewable Energy with Electrolysis Systems

PEM e2.7 critical electrolyzers are efficient at partial loads down to 5–10% of rated capacity and can ramp from zero to full load within milliseconds, which is inherently compatible with the rapid power fluctuations of wind generation. Alkaline elunits are electrolyzers, but electrolyzers have minimum stable load limits of approximately 20-40% of rated capacity, limiting flexibility for variable renewable energy coupling. Techno-economic analyses show that co-located solar PV and production and 5.6 degradation PEM electrolyzer systems in high-irradiance regions can achieve hydrogen costs of $2–4 per kg at 2024 capital cost levels. With continued learning on technology in line with the IEA Net Zero scenario, green hydrogen costs of $1.5–2.0/kg in high-resource regions by 2030 appear achievable (Cui et al., 2023; Eyro et al., 2024; Guo et al., 2024; Yongije, 2024; Yu et al., 2019)

Degradation Mechanisms and Durability Challenges

The most important commercial obstacle to PEMFCs in the automotive industry is durability. The degradation of platinum catalysts is caused by electrochemical dissolution at high potentials, Ostwald ripening of dissolved Pt ions, sintering of neighboring Pt nanoparticles, and detachment from the carbon-levelized support. These processes all lead to an increase in ORR overpotential and a decrease in electrochemically active surface area (ECSA). Reactive oxygen species (H_2O_2, •OH, •OOH) generated from incomplete O_2 reduction at the decentralized cathode and cathode as well as H_2 crossover from the anode via the Fenton method cause polymer membrane deterioration. CO_2 nanoparticles as radical scavengers, enlarged PTFE reinforcement for composite membranes, and Pt-Co or Pt-Ni alloy catalysts with improved dissolution resistance have all been suggested as solutions to this problem (Adeleye et al., 2026b, Amini et al., 2024; Cui et al., 2023; Eyro et al., 2024; Guo et al., 2024; He et al., 2020; Giang et al., 2024; 2022; Lei et al., 2024; Luo et al., 2022; Ma et al., 2021; Muik et al., 2024; Sebbahi et al., 2024; Singh et al., 2025)

VI. DISCUSSION AND CONCLUSION

Engineering Interpretation of Results

The results summarized in Section 5 describe a rapidly evolving technology ecosystem, with progress on many fronts but held back by a number of interconnected technical, economic, and infrastructural challenges. The most fundamental conclusion is that the hydrogen economy is not a single-technology proposition: no single type of fuel cell and no single hydrogen production method are universally optimal across all application domains. Rather, the evidence points to a niche multi-technology architecture with PEMFCs addressing the transport and distributed power markets, SOFCs addressing the high-temperature stationary CHP market, and MCFCs being used for industrial gas utilization and CO_2 capture. On the production side, PEM and alkaline electrolysis are the near-term workhorses, SOECs are the longer-term option for high-temperature industrial integration, and

thermochemical biomass conversion offers a cost-competitive near-term route in agricultural economies (Pang et al., 2024; Qi et al., 2023; Raja et al., 2021; Sezer et al., 2025; Sun et al., 2020; Vincent et al., 2021; Wang et al., 2025; Xu et al., 2022; Yu et al., 2022; Zhao et al., 2025; Zeng et al., 2025)

The economic numbers tell a story of an industry at a crossroads. Green hydrogen LCOH is $3–7 per kg in 2025, two to four times more expensive than grey hydrogen from SMR ($1.0–2.5 per kg), but the cost curve is sharply downward. The shown learning rate of 15–18% per doubling of installed 2.6 GW renewable electrolyzer manufacturing capacity suggests that if global electrolyzer installations continue to double every two to three years, LCOH in favorable locations could fall below $2.00 per kg by the late 2020s and be close to $1.50 per kg by 2030. This would make green hydrogen competitive with blue hydrogen in the high-resource regions and with grey hydrogen in the mid-2030s in the late 2020s. (Eyro et al., 2024; Guo et al., 2024; He et al., 2020; Giang et al., 2024; 2022; Lei et al., 2024; Luo et al., 2022; Ma et al., 2021; Muik et al., 2024; Sebbahi et al., 2024; Singh et al., 2025)

Catalyst and Materials Challenges

The platinum-group metals (PGM) reliance of the PEMFC and PEM electrolyser ecosystem constitutes one of the most important systemic risks to the large-scale rollout of the hydrogen economy. For PEMFCs, the platinum loading must be reduced below 0.1 mg cm−2 to achieve the DOE's cost goal of $80/kW. Research approaches include core-shell nanostructure catalysts that maximize the fraction of Pt atoms on the surface; Pt-transition metal alloy catalysts (Pt_3Ni, Pt_3Co) that exhibit 5–10× higher mass activity for ORR; and Pt-free catalysts based on iron-nitrogen-carbon (Fe-N-C) single-atom coordination sites (Lei et al., 2024; Luo et al., 2022; Ma et al., 2021; Muik et al., 2024; Sebbahi et al., 2024) The OER at the anode of PEM electrolyzers has to be catalyzed by iridium-based catalysts with enough activity and stability. The global annual iridium production is only 7–9 tonnes and is concentrated in South Africa. The deployment of large-scale PEM electrolysis will risk creating a critical supply constraint without dramatic reduction in iridium loading. A major challenge in electrochemical engineering research is to reduce the loading of iridium from the current 0.5–2.0 mg cm−2 to less than 0.1 mg cm−2 without sacrificing activity or stability. (Amini et al., 2024; Cui et al., 2023; Eyro et al., 2024; He et al., 2020; Hao et al., 2025; Luo et al., 2024; Pang et al., 2024; Qi et al., 2023; Raja et al., 2021; Sezer et al., 2025; Sun et al., 2020; Vincent et al., 2021; Wang et al., 2025; Xu et al., 2022; Yu et al., 2022; Zhao et al., 2025; Zeng et al., 2025)

Infrastructure, Systems Integration, and Sector Coupling

The development of a functional hydrogen economy requires not only efficient devices but also the concurrent and coordinated deployment of a whole new physical infrastructure for hydrogen production, compression, storage, long-distance transport, and dispensing. The state of this infrastructure is embryonic: as of early 2025, some 1,200 hydrogen refueling stations are in operation worldwide, mostly concentrated in Japan, South Korea, Germany, and California, which is utterly inadequate for enabling significant vehicle fleet deployment [3]. Individual station capital costs of $3–5 million and no high-pressure hydrogen pipeline network create significant entry barriers and perpetuate the chicken-and-egg dilemma (Guo et al., 2024; He et al., 2020; Giang et al., 2024; 2022; Lei et al., 2024; Luo et al., 2022)

We need public investment in shared infrastructure backbone assets—such as high-pressure hydrogen trunk pipelines, underground storage facilities, and large-scale centralized production plants—to break this impasse. The European Hydrogen Backbone initiative envisages the conversion of natural gas infrastructure into 53 000 km of hydrogen pipelines in 28 European countries by 2040 at an estimated cost of €80–143 billion. In Nigeria, where a centralized hydrogen infrastructure is a longer-term prospect, the priority should be to demonstrate decentralized green hydrogen production from solar PV and agricultural biomass at community and industrial scales whereby fuel cell CHP systems can provide reliable, clean electricity and heat (Pang et al., 2024; Qi et al., 2023; Raja et al., 2021; Sezer et al.,

2025; Sun et al., 2020; Vincent et al., 2021; Wang et al., 2025; Xu et al., 2022; Yu et al., 2022)

The vision of a hydrogen economy is not just the hydrogen economy itself, but the vision of sector coupling—the close integration of the power sector, gas network, heating sector, transport sector, and industrial processes through hydrogen as the common energy carrier. The long-term costs of decarbonization are consistently found to be substantially lower in scenarios with hydrogen sector coupling than in scenarios with only direct electrification, particularly for hard-to-abate sectors (Giang et al., 2024; 2022; Lei et al., 2024; Luo et al., 2022; Ma et al., 2021)

Comparison with Literature and Institutional Projections

The cost and performance results of this review are consistent with the most authoritative institutional assessments. The IEA's 2023 Global Hydrogen Review estimates that green hydrogen costs will range from $2-6 per kg by 2030, depending on the cost of renewable electricity and the speed of electrolyser cost reduction. The DOE's Hydrogen Shot goal of $1 per kg by 2031 is only feasible under the most optimistic assumptions, and a more realistic assessment based on recent projections indicates $2–3 per kg in best-resource regions by 2030. The potential of biomass-derived green hydrogen as a near-term cost-competitive pathway is in line with Awogbemi et al., 2024 and Adeleye et al., 2024 and more general renewable energy prospects for Nigeria. The techno-economic feasibility of bio-digester-based biogas systems and solar PV-biomass hybrid systems in the Nigerian context further supports the case for a diversified, regionally appropriate approach to green hydrogen deployment in sub-Saharan Africa. (Hao et al., 2025; Luo et al., 2024; Pang et al., 2024; Qi et al., 2023; Raja et al., 2021; Sezer et al., 2025; Sun et al., 2020; Yu et al., 2022; Zhao et al., 2025; Zeng et al., 2025)

Limitations of the Review

This review has several inherent limitations. The techno-economic results vary greatly between studies depending on the regional electricity price, discount rate, stack lifetime, capacity factor, and the year of the analysis. The ranges reported here should be taken as indicative compass headings and not as exact coordinates. Due to the lack of long-term experimental data, coverage of emerging technologies, such as AEM electrolyzers, high-entropy oxide OER catalysts, and biological hydrogen production, is necessarily limited. While we screened over 220 sources and employed a systematic search strategy, there remains the possibility of some publication bias toward positive results in the primary literature. A discussion of the policy and deployment context in Nigeria is provided at a level of generality suitable for a review paper; site-specific and community-level evaluations would require specific primary research.

Conclusion

This comprehensive review critically discusses the current technological status, fundamental electrochemical principles, diverse applications, engineering challenges, and long-term future prospects of fuel cells and renewable hydrogen. Five major conclusions are drawn from a systematic synthesis of more than 220 sources, including peer-reviewed literature, institutional roadmaps, and techno-economic analyses published between 2020 and 2025.

First, fuel cells have grown from laboratory curiosities into a healthy and diverse family of commercial electrochemical energy converters. The high-power density (0.8–1.2 W cm^{-2}), fast dynamic response, and proven automotive reliability of PEMFCs have earned them a position of prominence in the transportation and distributed power markets. SOFCs in stationary CHP configurations provide the highest total energy utilization with system efficiencies greater than 85–90%. PAFCs have shown extraordinary operational longevity of more than 80,000 hours. MCFCs offer a unique solution to utilize industrial waste gases and capture CO_2. AFCs are experiencing a renaissance with the development of AEMs that could allow for PGM-free electrochemical energy conversion. Crucially, there is no one technology that will be a panacea, and the commercial hydrogen economy will be developed on a complementary ecosystem of all five technologies.

Second, the cost curve of green hydrogen has shifted decisively from academic aspiration to commercial reality. Since 2015, the costs of PEM and alkaline electrolysis have fallen by above 50% due to a learning rate of 15–18% per doubling of installed capacity, which is expected to continue. Green hydrogen is expected to become cost-competitive with blue hydrogen in high-resource regions by the late 2020s and with grey hydrogen in the mid-2030s. The thermochemical conversion of agricultural biomass presents an alternative production route, particularly relevant to agricultural economies, offering competitive costs and co-benefits for waste management (Adeleye et al., 2026a; Amini et al., 2024; Cui et al., 2023; Eyro et al., 2024; He et al., 2020; Hao et al., 2025; Luo et al., 2024; Pang et al., 2024; Qi et al., 2023; Raja et al., 2021; Sezer et al., 2025; Sun et al., 2020; Vincent et al., 2021; Wang et al., 2025; Xu et al., 2022; Yu et al., 2022; Zhao et al., 2025; Zeng et al., 2025)

Third, the role of fuel cells and green hydrogen in the global decarbonization is much more than just the generation of electricity. Hydrogen is the main tool for decarbonizing hard-to-abate sectors, including heavy-duty transport, steel production, ammonia synthesis, and maritime shipping. Power-to-Gas provides the needed energy bridge between summer renewable surpluses and winter peak demand, a prerequisite for near-100% renewable electricity systems, enabling seasonal energy storage at costs and scales beyond the reach of battery technologies.

Fourth, critical bottlenecks must be overcome for the hydrogen economy to achieve its transformative potential. The most important material supply risks are the shortage of iridium for PEM electrolysis OER catalysts and the dependence of automotive PEMFCs on platinum. To achieve commercial targets, the durability of membranes and catalysts under realistic operating conditions needs to be extended by 2–3 times. The existing global hydrogen distribution and refueling infrastructure is completely insufficient to the scale of deployment required and requires unprecedented levels of coordinated public and private investment.

Fifth, the hydrogen economy offers specific opportunities for Nigeria and sub-Saharan Africa where a confluence of abundant renewable energy resources, large agricultural waste streams, significant energy access deficits, and growing international demand for green hydrogen exports presents a strategic development opportunity. Decentralized solar PV and biomass-based green hydrogen production together with renewable fuel cell CHP deployment can simultaneously advance SDG 7 objectives and contribute to national climate commitments (Adeleye et al., 2026a; Amini et al., 2024; Cui et al., 2023; Eyro et al., 2024; He et al., 2020; Hao et al., 2025; Luo et al., 2024; Pang et al., 2024; Qi et al., 2023; Raja et al., 2021; Sezer et al., 2025; Sun et al., 2020; Vincent et al., 2021; Wang et al., 2025; Xu et al., 2022; Yu et al., 2022; Zhao et al., 2025; Zeng et al., 2025)

Renewable hydrogen and fuel cells are not fringe technologies in the clean energy transition; they are integral building blocks of carbon-neutral global energy architecture. In summary, the pace of innovation and infrastructure investment needs to be further accelerated to meet the Net Zero 2050 challenge within the time window demanded by climate science.

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