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Renewable Energy Technology: Fuel Cell Application for Electricity Generation

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Abstract: *The Nigerian energy sector has long struggled to provide adequate electricity to meet the country's growing population demand. Challenges in generation, transmission, and distribution have resulted from several factors, including the nation's economic structure dominated by agriculture and crude oil, and the lack of essential physical infrastructure. To enhance industrial growth and ensure reliable power supply, this study proposes exploring alternative energy solutions such as fuel cell technology. Fuel cells offer high efficiency, low emissions, scalability, and minimal mechanical complexity. Moreover, local adoption and production of fuel cells could generate employment, stimulate industrial activities, and strengthen Nigeria's economy.*

KEYWORDS: Renewable energy, fuel cell, electricity, electrochemical reaction

INTRODUCTION

Nigeria's first encounter with electricity generation commenced in Lagos in 1896, a mere fifteen years after its introduction in England [1]. The initial power plant, with a modest capacity of 60 kW, adequately served the city's early needs. The sector's institutional foundation was laid in 1946 with a government electricity project under the Public Works Department (PWD) for Lagos [2]. This evolved in 1950 with the establishment of the Electricity Corporation of Nigeria (ECN), created as a centralized body for nationwide generation and supply [3]. Alongside the ECN, other licensed entities like the Nigerian Power Supply Company (NESCO) also operated.

A significant development was the subsequent creation of the Niger Dams Authority (NDA), tasked with constructing dams for hydropower, as well as irrigation and navigation [3]. The ECN acted as the distributor for the power produced by the NDA. To consolidate the sector, the operations of the ECN and NDA were merged in April 1972, forming the National Electric Power Authority (NEPA). This strategic merger unified the NDA's responsibility for building power stations and transmission lines with the ECN's core functions of distribution and sales, creating a single, state-owned utility monopoly [2].

Despite the National Electric Power Authority's (NEPA) annual expansion, reliable electricity remained elusive for most Nigerians [4]. This chronic inadequacy prompted the Federal Government to embark on major reforms. NEPA was first restructured into the Power Holding Company of Nigeria (PHCN). The pivotal 2005 Electric Power Sector Reform Act then dismantled the state-owned monopoly, unbundling it into 18 separate companies: six for generation, eleven for distribution, and one for transmission [5]. This restructuring transferred ownership to the Bureau of Public Enterprises (BPE), paving the way for privatization. Guided by international consultants, the BPE led this process to its conclusion, achieving the full privatization of PHCN on September 30, 2013, under President Goodluck Jonathan [6][7].

With the reforms and investment, widespread power outages persist in Nigeria. The nation's operational output of roughly 2,000 MW from a 6,000 MW installed capacity is critically inadequate for its population of over 150 million. This stark deficit, especially when compared to nations like Finland [8], which generates 36,000 MW for 5.5 million people, stems from crumbling infrastructure, poor maintenance, and an overdependence on crude oil. The unreliable grid has normalized mass generator importation, a lucrative trade some reports suggest benefits the political elite. While generator use raises pollution concerns, simply banning imports is not a solution [8][9]. The government must instead address root causes by investing in grid infrastructure, modern technologies, and diversifying into cleaner alternatives like fuel cells.

Ultimately, reliable electricity is fundamental to Nigeria's economic future. Achieving sustainable development hinges on strengthening the energy sector through consistent policy, infrastructure expansion, and the adoption of innovative technologies.

II. ELECTRICITY GENERATION CHALLENGES IN NIGERIA

For over forty years, Nigeria's electricity generation has been sourced from a combination of gas, oil, hydro, and coal-fired power plants, with hydroelectric power historically playing the most significant role. This diversified energy mix is supported by the nation's substantial natural resources, including extensive coal reserves and vast natural gas deposits. The latter, estimated at 2.4 trillion cubic meters [10], are twice the size of Nigeria's crude oil resources and represent a critical domestic and export fuel for the coming century.

However, the reform of Nigeria's power sector, essential for a developing economy, is fraught with complex challenges. These obstacles are broadly categorized as economic, social, technical, political, and environmental [11]. The core objective of the Federal Government's reform agenda is to achieve a more efficient, reliable, and affordable electricity supply. A major strategy involves rehabilitating non-operational power units and expanding the overall generation capacity. To meet rising demand and ensure economic stability, a collaborative effort is required to construct new power plants, involving the government, the Power Holding Company of Nigeria (PHCN), and Independent Power Producers (IPPs). However, constructing and maintaining power infrastructure is capital-intensive [12], leading to potential increases in electricity tariffs and possible job losses following mergers and privatization [13]. Beyond generation, attention must also be given to transmission capacity and energy utilization efficiency. Expanding and reinforcing transmission lines, particularly in areas where IPPs operate close to energy sources, is crucial. Additionally, implementing Demand Side Management (DSM) programs can help optimize electricity consumption by encouraging consumers to adjust usage patterns rather than expanding generation capacity. DSM initiatives, such as incentive-based programs for households, industries, and institutions, should be evaluated based on their cost-effectiveness compared to building new plants and transmission systems [14][15]. Creating a stable and transparent investment environment is vital for attracting private sector participation. Many IPPs prefer to establish plants in the Niger Delta due to its proximity to fuel resources; however, regional instability, militancy, and youth unrest pose major risks. Sustaining democratic governance and ensuring policy consistency are therefore essential for investor confidence and long-term energy sector growth [12][16].

Environmental considerations also influence plant siting decisions. Industrial cities with high carbon emissions may resist additional thermal plants. To mitigate pollution, the government should empower Environmental Inspection Agencies (EIAs) to monitor and regulate industrial impacts. Moreover, IPPs often face high compensation costs for land acquisition, economic trees, and right-of-way clearances, which can discourage investment [13]. In light of these challenges, fuel cell technology presents a viable alternative for electricity generation in Nigeria. Fuel cells offer clean, efficient, and scalable power solutions that can be locally manufactured. Their adoption could not only reduce environmental pollution but also create employment opportunities and stimulate local technological innovation in the power sector.

III. FUEL CELL TECHNOLOGY

A fuel cell is an electrochemical device that directly converts chemical energy into electrical energy. It operates like a cross between a battery and an engine, generating power through reactions involving a fuel and oxygen. The core components are two electrodes, an anode and a cathode, separated by an electrolyte, with a catalyst to speed up the reaction. While hydrogen is the primary fuel, alternatives like natural gas or methanol can be used. Major distinction from batteries is that fuel cells do not store energy but produce a continuous supply of electricity as long as fuel and oxygen are supplied.

Despite their modern perception, fuel cells have a long history. The foundational principle was first proposed by German scientist Christian Friedrich Schönbein in 1838 [17]. Shortly after, in 1839, Welsh scientist Sir William Robert Grove built the first working prototype [18]. He published his findings, and his early design remarkably used materials similar to those in contemporary phosphoric acid fuel cells. The evolution of this technology from Grove's initial invention to the present day is outlined in Figure 1.

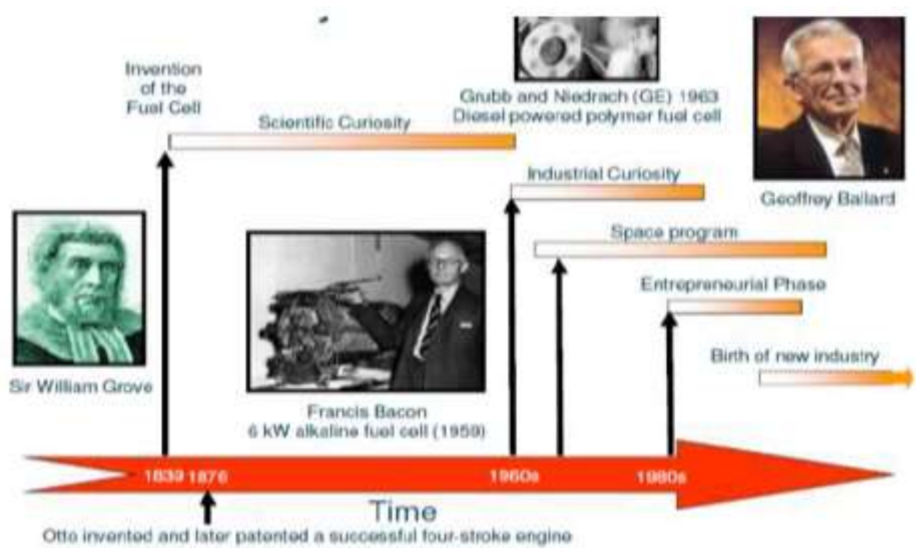

Figure 1: History of fuelcell development [19]

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At its core, a fuel cell's essential component is the unit cell, which electrochemically converts a fuel's chemical energy into electricity. As shown in Fig. 2, each cell has a fundamental structure: an electrolyte layer positioned between two electrodes, the anode and the cathode.

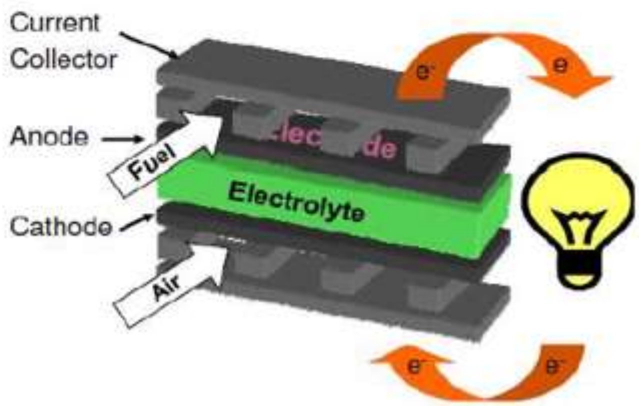

Figure 2: Basic Structure of a Typical Fuel cell [19]

In a standard fuel cell, a continuous flow of fuel is supplied to the anode (the negative electrode) and an oxidant, such as oxygen from air, is fed to the cathode (the positive electrode). Electrochemical reactions at these electrodes produce an electric current, which passes through the electrolyte to power an external circuit.

Although fuel cells and batteries are both electrochemical devices, they operate on a fundamentally different principle. A battery is a closed energy storage system with a finite supply of reactants, which depletes over time. A fuel cell, however, is an open energy conversion system; it generates electricity continuously as long as fuel and oxidant are supplied from an external source. Fuel cells are classified primarily by their electrolyte material, which dictates the electrochemical reactions, the type of ions that carry the current, and their operating temperature, a range that spans from ambient to over 1000°C (see Fig. 3). The six main types [20] include Proton Exchange Membrane (PEMFC), Alkaline (AFC), Phosphoric Acid (PAFC), Molten Carbonate (MCFC), Solid Oxide (SOFC), and Direct Methanol (DMFC) fuel cells.

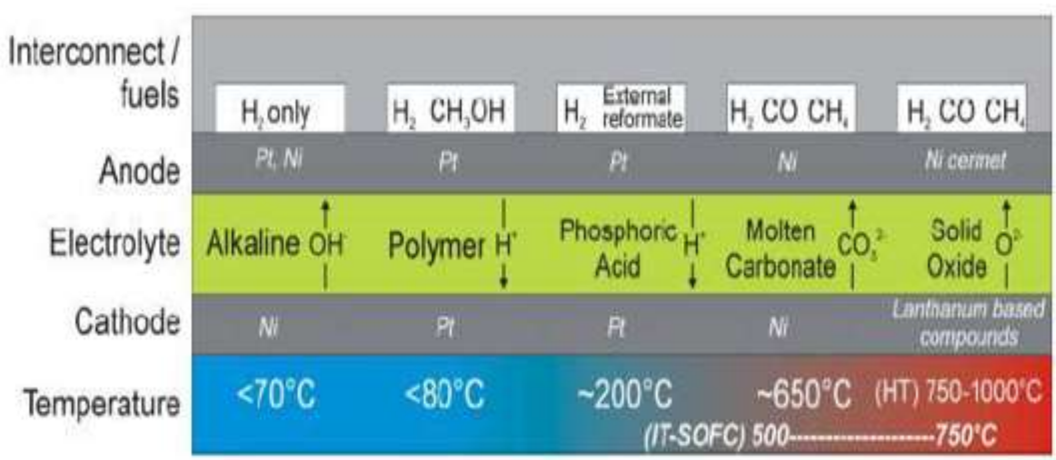

Figure 3: Fuel cell system and operating temperature range [19]

The choice of electrolyte is the primary factor in determining a fuel cell's operating temperature. This temperature, along with the desired lifespan, dictates the essential physical and chemical properties needed for all core components, such as the electrodes, electrolyte, interconnects, and current collectors. For example, aqueous electrolytes are confined to temperatures below 200°C due to high vapor pressure and rapid degradation.

The operating temperature also governs the level of external fuel processing required. Low-temperature fuel cells, which often use platinum catalysts, are highly susceptible to carbon monoxide poisoning and must be supplied with pure hydrogen. In contrast, high-temperature fuel cells with nickel-based catalysts are more tolerant and can even internally reform fuels like methane into hydrogen directly [21].

Major advantage of fuel cells is their direct, combustion-free conversion of chemical energy to electricity, which results in high efficiency and minimal emissions. Their primary benefits include:

1. High energy efficiency
2. Minimal or no emissions
3. Quiet, reliable operation with no moving parts
4. Scalability, suitable for power outputs ranging from milliwatts (mW) to megawatts (MW) [19].

IV. APPLICATION OF FUEL CELL FOR ELECTRICITY GENERATION

A fuel cell is a type of galvanic cell that directly converts a fuel's chemical energy into electricity via electrochemical reactions [22]. It operates by continuously supplying a fuel and an oxidant to two separate electrodes. An electrolyte layer between these electrodes facilitates the transfer of ions, completing the internal circuit (see Fig. 4).

During operation, the fuel is oxidized at the anode with the aid of a catalyst, releasing electrons. These electrons are then driven through an external circuit by the potential difference between the electrodes, creating an electric current. Upon reaching the cathode, the electrons combine with oxygen and ions to form the final reaction products.

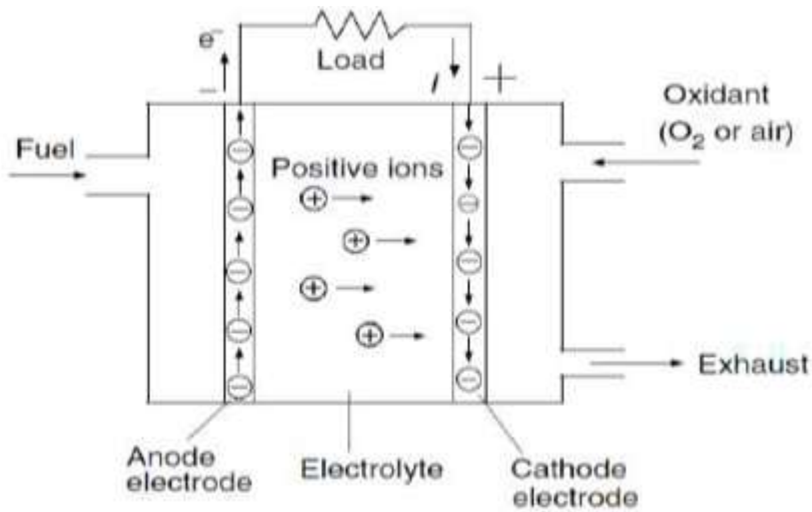

Figure 4: Basic operation of a fuel cell [12]

The chemical processes in a fuel cell are analogous to those in a conventional battery. The thermodynamic voltage of the cell is determined by the energy released in the reaction and the number of electrons transferred. This energy is quantified by the change in Gibbs free energy (ΔG), usually given per mole of reactant.

For an electrochemical reaction to generate electricity, specific components are essential: electrodes where oxidation (at the anode) and reduction (at the cathode) occur; an electrolyte that permits ion transfer but blocks electron flow; and an external circuit to allow for current. Reactions that produce an electric current in this way are termed galvanic, a category that includes both fuel cells and batteries.

As shown in Figure 5 for a polymer electrolyte fuel cell, the process enables a continuous current, unlike a standard chemical reaction. The fundamental global reactions driving this process are the Hydrogen Oxidation Reaction (HOR) at the anode and the Oxygen Reduction Reaction (ORR) at the cathode [19].

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \qquad (1)$$

But electrochemically

$$H_2 \rightarrow 2H^+ + 2e^- \qquad \text{(HOR)} \qquad (2)$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \qquad \text{(ORR)} \qquad (3)$$

Charge neutrality (an excess of charge cannot be maintained in equilibrium

$$H_2 \rightarrow 2H^+ + 2\,e^- \qquad \text{(HOR)} \qquad (4)$$

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow 2H_2O \qquad \text{(ORR)} \qquad (5)$$

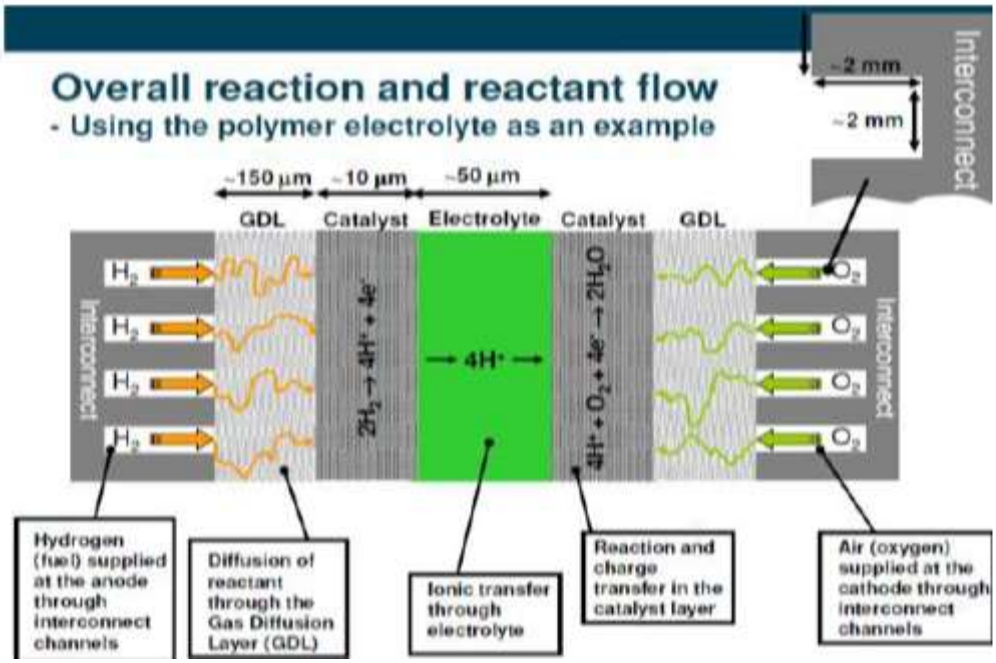

Figure 5: Overall reaction and reactant flow using polymer electrolyte [19]

Fuel Cell Model

It is essential to analyze and derive the mathematical expressions for each of these losses to effectively model the fuel cell and accurately predict its performance. Therefore:

$$E = E^O + \frac{RT}{nF} In \frac{\Pi^{V_I}_{reactant}}{\Pi_{PRODUCT}} \qquad (6)$$

Where $E^o = \frac{-\Delta G^o}{nF}$, $\Pi^{V_i}_{a\,reactant} = aH_2(a_{02})^{\frac{1}{2}}$, $\Pi^{V_i}_{a\,produc} = aH_2O$

$$E = \frac{-\Delta G^o}{nF} + \frac{RT}{nF} In \frac{aH2 \;\; (a_{o2})^{\frac{1}{2}}}{aH_2O} \qquad (7)$$

$$E = -\frac{\Delta G^o}{nF} + \frac{RT}{nF} In \frac{(\frac{YH_2P_{onoe}}{P_O})(\frac{YO_2P_{cathode}}{P_O})^{\frac{1}{2}}}{(\frac{YH_2P_{cathode}}{P_O})} \qquad (8)$$

From thermodynamic

$$\Delta G^O = \Delta H - T\Delta S,\; \Delta H = \int_{To}^{T} C_P(T)dt \;\; and \; \Delta S = \int_{To}^{T} \frac{C_p(T)}{T} dT \quad (9)$$

$$V = E^o - n_{act} - n_{ohmic} - n_{come}\Pi \qquad (10)$$

It is essential to analyze and derive the mathematical expressions for each of these losses to effectively model the fuel cell and accurately predict its performance. Therefore:

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$$\eta_{act} = [a_A + b_A \ln(j + j_{leak})] + [a_C + b_C \ln(j + j_{leak})] \quad (11)$$

$$\eta_{ohmic} = j \cdot ASR_{orhmic} \quad \text{and} \quad \eta_{conc} = c * ln \frac{j_L}{j_L - j - j_{leak}} \quad (12)$$

Substituting equations 10 and 11 into 9 gives an overall equation

$$V = E^0 - [a_A + b_A \ln(j + j_{leak})] + [a_C + b_C \ln(j + j_{leak})] - (j \cdot ASR_{ohmic}) - \left(c * ln \frac{j_L}{j_L - j - j_{leak}}\right) \quad (13)$$

Where
ASR_{ohmic} = Area specific Resistance; A_f = Frontal area;
C_D = Aerodynamic drag coefficient; E_{cell} = Electric potential of the cell;
E^{00} = Thermal Voltage; f_r = Rolling resistance coefficient;
g = Acceleration due to gravity; c = Empirical constant from Mass transport losses;
ΔG^0 = Gibbs free energy; ΔH = Change in Enthalpy;
ΔS = Change in Entropy; F = Faraday's Constant;
j_o = Exchange current density; n = Number of moles;
η_t = Transmission efficiency; ρ_a = Air density;
α = Charge Transfer Coefficient; V = velocity

Fuel cell performance and operation are commonly assessed using a polarization curve (see Fig. 6), which depicts the irreversible losses and the deviation from the ideal Nernst voltage. These deviations result from factors such as species crossover through the electrolyte, internal current flow due to electron leakage, and the presence of contaminants. Generally, the efficiency of a fuel cell is affected by three major loss mechanisms: kinetic losses from electrode reaction rates, Ohmic (IR) losses caused by resistance to electronic and ionic conduction, and concentration polarization arising from limitations in mass transport. These losses constitute the main challenges in utilizing fuel cells for power generation, as excessive losses can greatly hinder overall performance. Typically, the operating voltage of a fuel cell lies between 0.65 V and 1.0 V.

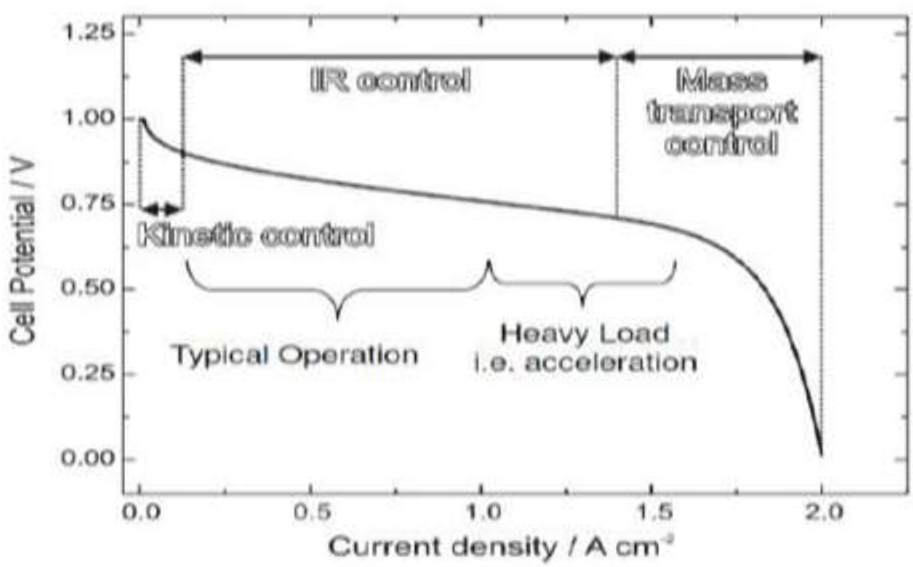

Figure 6: Fuel cell polarization Curve [19]

This study provides an in-depth examination of fuel cell technology and its prospective applications within Nigeria. Fuel cells offer high efficiency and emit far fewer pollutants than conventional energy generation systems, making them promising candidates for clean and reliable electricity production in the country. Moreover, their operation is less vulnerable to disruptions caused by vandalism or social unrest compared to gas-powered generators.

With focused investment in research, development, and deployment, and by identifying suitable sectors for implementation, fuel cell technology could serve as a catalyst for economic expansion and national prosperity. Its adoption could facilitate Nigeria's transition to a hydrogen-based energy economy, boost electricity generation, and create numerous technical and industrial employment opportunities. Additionally, establishing production facilities, manufacturing components, and marketing related equipment could generate profitable ventures that support job creation and stimulate economic growth.

Despite these advantages, several challenges still hinder large-scale adoption. One major issue lies in the fueling process, as hydrogen production, transportation, distribution, and storage remain technically complex. Producing hydrogen through hydrocarbon reforming also presents both environmental and technical obstacles. Furthermore, fuel cell vehicles currently face limitations such as longer refueling times, shorter travel ranges, and larger system sizes compared to conventional combustion engine vehicles, though ongoing innovations are addressing these concerns. Another constraint is the high cost of production since most fuel cells are still manually assembled. The technology is still in the developmental phase, with only a few commercially available products on the market.

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