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Engineering Technology in Renewable Energy: A Comprehensive Review of Solar, Wind, and Hybrid System

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ABSTRACT

Nigeria's electricity sector continues to experience persistent challenges including inadequate supply, fragile grid infrastructure, fuel dependency, and exposure to economic and climatic shocks. At the same time, the country is endowed with vast renewable energy resources and stands at a critical juncture in its energy transition. This paper examines emerging renewable energy technologies and strategic pathways for building resilient power systems in Nigeria. Drawing on synthesized evidence from peer reviewed literature, international policy reports, energy transition frameworks, the study explores advances in solar, wind, hybrid systems, digitalisation, energy storage, and hydrogen technologies. It further discusses strategic pathways such as distributed generation, smart grid deployment, institutional reforms, and long term transition planning. The paper argues that integrating emerging technologies with coherent policy, robust governance, and inclusive planning is essential for developing a resilient renewable based power system capable of supporting Nigeria's socio economic development and climate goals.

Keywords— **Emerging technologies, Energy transition, Engineering Technology, Renewable energy, smart grids, Nigeria**

I. INTRODUCTION

Electricity supply remains one of the most critical constraints to Nigeria's economic growth and social development. Despite an installed grid capacity of approximately 13Gigawatt (GW), effective available generation typically averages below 5GW due to gas supply limitations, aging infrastructure, hydrological variability, and transmission bottlenecks (International Renewable Energy Agency [1]. Consequently, households and industries rely heavily on diesel and petrol generators, resulting in high energy costs, environmental degradation, and reduced economic competitiveness. Globally, energy systems are undergoing rapid transformation driven by declining renewable energy costs, technological innovation, and the urgency of climate change mitigation. For Nigeria, this transition presents a strategic opportunity to diversify its energy mix, enhance system resilience, and expand access to affordable electricity. Emerging renewable energy technologies, when integrated with modern grid infrastructure and enabling policy frameworks, can address long standing structural weaknesses in the power sector [2]. This paper examines emerging technologies and strategic pathways for resilient renewable power systems in Nigeria. However, recurring issues such as gas shortages, outdated infrastructure, seasonal water scarcity, and limited grid capacity continue to hamper progress [3] By synthesising insights from technology reviews, national energy roadmaps, and energy transition literature, the study provides a comprehensive perspective on how Nigeria can strengthen power system resilience while advancing sustainable development objectives.

II. MATERIALS AND METHODS

The study adopted a quantitative descriptive research design to systematically evaluate the effectiveness and performance of Engineering Technology in Renewable Energy, and the effectiveness of Hybrid Renewable Energy Systems (HRES), specifically those integrating solar, hydro, and wind energy sources. This methodological approach enabled the researchers to collect, measure, and analyze numerical data, ensuring an objective evaluation of energy output efficiency, environmental benefits, and cost-effectiveness associated with hybrid systems. A key advantage of this design is its ability to provide statistical insights into patterns and trends, facilitating a deeper understanding of how HRES contribute to energy availability.

A. Baseline Assessment of Nigeria's Power System Capacity and Reliability

Figures 1 to 4 establish the empirical baseline against which the case for emerging renewable energy technologies is built in this study. Taken together, they trace the supply chain of Nigeria's electricity system, from installed capacity through to what actually reaches the end user, revealing where the largest losses of capacity occur. Fig. 1 compares installed, available, transmission, and generation capacities against peak load demand, and shows that each stage of the value chain sheds capacity, so that what is actually generated and transmitted falls well short of both the nameplate installed figure and the demand it is meant to serve [4]. This pattern is not an isolated snapshot: Fig. 2 extends the comparison across a full year and shows that grid supply remains persistently and substantially below demand in every month, indicating that the deficit observed in Fig. 1 is a chronic structural condition rather than a seasonal or transient anomaly [5].

Fig. 3 explains part of the reason for this shortfall by quantifying losses within the distribution network itself: of the available capacity, only a fraction is actually delivered to consumers, yielding a system efficiency of about 60% and roughly 1,800 MW of technical and non-technical losses [5]. This finding demonstrates that Nigeria's power deficit is driven not only by insufficient generation but also by inefficiencies in transmission and distribution infrastructure, reinforcing the resilience concerns raised in Fig. 5 and the accompanying discussion. Fig. 4 then illustrates the consumer-side consequence of this combined generation and delivery shortfall: private, decentralised generation accounts for the majority (73%) of electricity actually consumed, compared with only 27% supplied directly through the grid [6], [7]. Read together, Figures 1 to 4 show a coherent picture of a power system that is constrained at every stage, generation, transmission, distribution, and delivery, and that has pushed households and industries toward self-generation as a coping mechanism. This baseline underscores the rationale for the renewable energy technologies and hybrid system pathways examined in subsequent sections, which are positioned as means of closing the capacity gap, reducing distribution losses, and easing dependence on costly, carbon-intensive private generation.

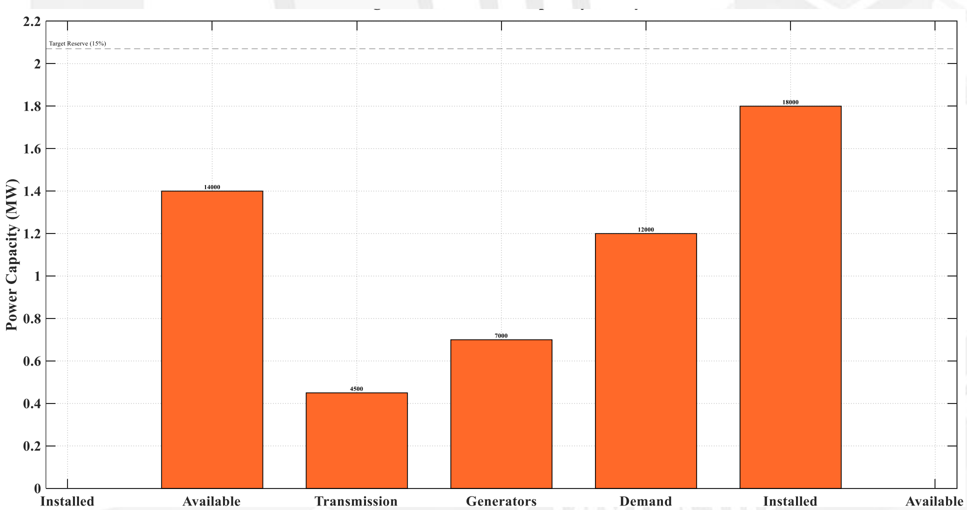

Figure 1: Comparative analysis of Nigeria's power system capacity levels showing installed (~1.8 MW), available (~1.4 MW), transmission (~0.45 MW), and generation capacities versus peak load demand (~1.2 MW), illustrating infrastructure constraints and operational deficits [4].

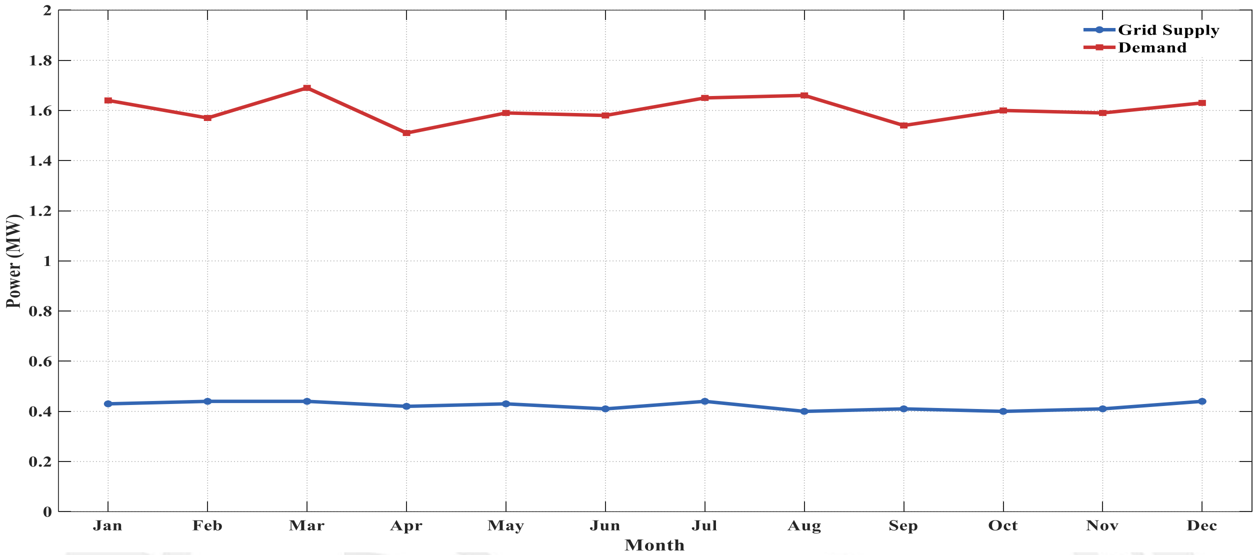

Figure 2: Monthly profile showing persistent supply-demand mismatch in Nigeria's power sector, with grid supply averaging ~0.4 MW against demand of ~1.6 MW throughout the year, indicating a significant baseline deficit [5]

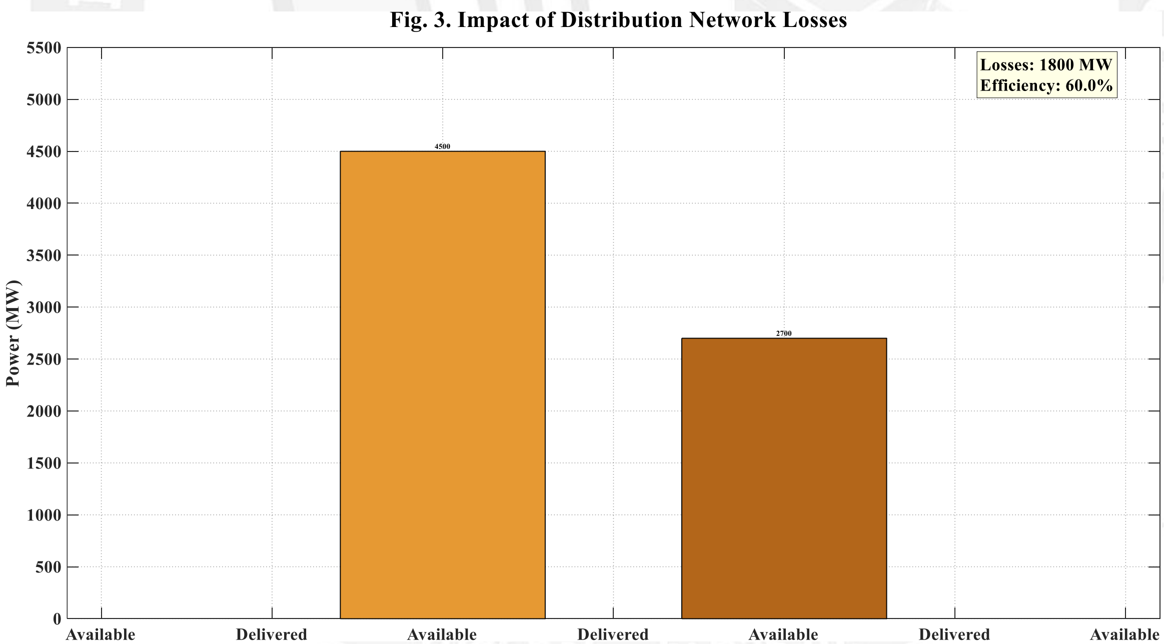

Figure 3: Evaluation of power delivery efficiency in Nigerian distribution networks, demonstrating technical and non-technical losses with available capacity (~4,500 MW) versus delivered capacity (~2,700 MW), resulting in 60% system efficiency and 1,800 MW losses [5].

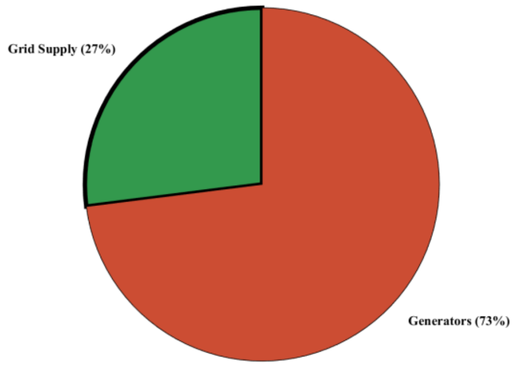

Figure 4: Nigeria's electricity composition showing 27% from grid supply versus 73% from private generators, highlighting heavy reliance on decentralized backup generation due to grid unreliability [6].[7].

B. Power System Resilience and Energy Transition

Power system resilience refers to the ability of an electricity system to anticipate, absorb, adapt to, and recover from disruptions such as equipment failures, fuel supply shocks, cyber threats, and extreme weather events. In renewable-dominated systems, resilience is closely linked to system flexibility, diversity of energy sources, decentralisation, and digital control capabilities [8]. The data in Figure 5 confirms that the current power system is trapped in a state of chronic "Partial Recovery" due to the unmitigated impact of System Stressors like equipment failure and transmission bottlenecks. The lack of Resilience Attributes specifically the absence of operational Flexibility to meet the 18,000 MW demand and a 40% loss in distribution prevents the transition to a stable energy future. As per [9], overcoming these stressors requires a shift toward Decentralisation and Digitalisation to bridge the massive 13,500 MW supply-demand gap.

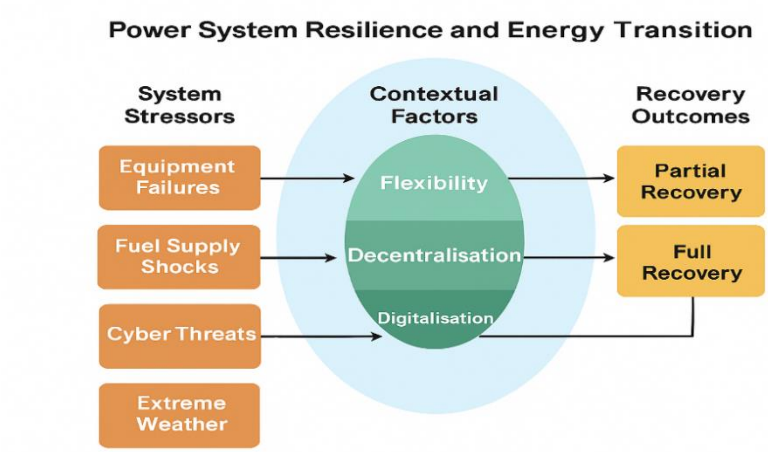

Figure 5: Conceptual framework of power system resilience and energy transition pathways, illustrating the relationship between system stressors, contextual mitigation factors, and recovery outcomes. (Source: [8])

C. Emerging Renewable Energy Technologies Relevant to Nigeria

(i) Solar Energy Technologies

Nigeria possesses one of the largest solar energy potentials in Africa, with average solar irradiation levels between 1,600 and 2,200 kWh/m² annually. The intensity of solar radiation is well distributed within the country [10]. During the day it is estimated Nigeria receives about 4.851 x 1012 kWh of energy from the sun, which is equivalent to about 1.082 million tons of oil per day. While domestic consumption of oil is 297 thousand barrel per day. When we change barrels into tones, we see very exiting number; 297000 barrels = 47219.2281 tons. It is obviously seen that domestic demand for oil can be substituted by solar energy [11], [12].

The 210 GW solar potential (IRENA, 2023) across Nigeria's high-irradiance zones serves as a critical contextual factor to mitigate the stressors identified in Figure 5. By integrating advanced PV technologies [9], the system can achieve the decentralization and flexibility required to bridge the current 13,500 MW deficit. This strategic deployment transition effectively moves the national energy profile from chronic "Partial Recovery" toward a resilient and inclusive "Full Recovery" outcome.

The evolution from conventional 15% efficiency modules to bifacial and tracking systems, culminating in emerging perovskite cells that exceed 30% efficiency [13] (Figure 6), represents a significant technological advancement in photovoltaic technology. Bifacial modules on dual-axis trackers have demonstrated 14% higher annual energy production compared to monofacial counterparts, with gains reaching up to 40% during winter months. This technological progression is further enhanced by AI and machine learning for optimized forecasting and fault detection, facilitating smoother grid integration. When combined with battery storage, these advanced PV systems offer a highly viable solution for Nigeria's expanding off-grid and mini-grid markets [14].

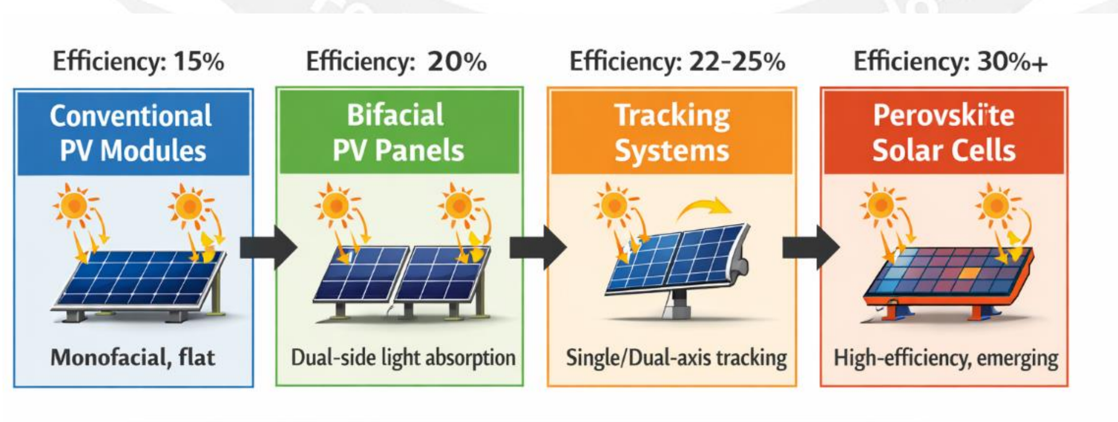

Figure 6: Evolution of photovoltaic technologies and their corresponding conversion efficiencies [13].

(ii) Wind Energy and Hybrid Systems

Nigeria's wind energy potential is moderate but geographically significant, particularly in northern and coastal regions. The estimated technical onshore wind potential is approximately 3.2 GW[18]. Technological improvements in turbine design, power electronics, and condition monitoring systems have enhanced reliability and reduced operational challenges. Hybrid renewable energy systems that combine wind, solar, and energy storage offer enhanced resilience by smoothing variability and improving supply reliability. Such systems are well suited for rural electrification, industrial clusters, and critical infrastructure, where uninterrupted power supply is essential [2].

(iii) Energy Storage Technologies

Energy storage is a cornerstone of resilient renewable power systems. Battery energy storage systems, pumped hydro storage, and emerging long duration storage technologies provide balancing services, frequency regulation, and backup power [15]. Advances in lithium ion, sodium ion, and supercapacitor technologies are improving performance while reducing costs [9]. In Nigeria's context of frequent outages, coupling storage with renewable generation can significantly reduce reliance on diesel generators for households, healthcare facilities, and small businesses. Table 1 shows the performance improvements of HRES when compared to single renewable systems.

Table 1: Performance Improvements of HRES Compared to Single Renewable Systems

Energy System Combination	**Performance Metric**	**Mean Score**	**Improvement (%)**	**Implications for Energy Production**
Solar + Wind + Biomass	Energy Output Efficiency	4.2	25%	Enhanced energy output allows for meeting higher demand.
Solar + Wind	Energy Reliability	3.8	20%	Increased reliability minimizes outages and fluctuations.
Solar + Biomass	Resource Utilization	3.5	15%	More effective use of available resources reduces waste.
Wind + Biomass	System Synergy	3.6	18%	Synergistic effects lead to improved overall system performance.

(Source: [16])

(iv) Hydrogen and Emerging Energy Hybrid

A typical hybrid system combines two or more energy sources, from renewable energy technologies such as PV-panels, wind or small-hydro turbines; and from conventional technologies usually diesel generator sets. In addition, it includes power electronics and electricity storage bank [17]. Renewable hydrogen produced via electrolysis using renewable electricity is increasingly recognised as a strategic energy carrier for long term storage and sector coupling. Hydrogen can support decarbonisation of hard to abate sectors and provide seasonal energy storage [2],[9]. Although hydrogen deployment in Nigeria remains nascent, it represents a long term opportunity within a resilient energy transition pathway

III. RESULTS AND DISCUSSION

The findings show that Figures. 1, 2, and 3 illustrate Nigeria's power grid capacity across generation, transmission, and distribution, highlighting the power losses caused by long transmission distances. In contrast, Table 1 shows that Hybrid Renewable Energy Systems (HRES) significantly enhance energy output efficiency, reliability, and resource utilization compared to single-source renewable systems. Combining multiple energy sources produced the highest efficiency gains: 25% for Solar + Wind + Biomass, 20% for Solar + Wind, 18% for Wind + Biomass, and 15% for Solar + Biomass, underscoring the synergistic potential of hybrid configurations. While solar and wind are highly sustainable, both are subject to intermittency; integrating biomass provides a steady baseline supply that sustains generation even when solar or wind conditions are unfavourable. This balanced structure minimizes fluctuations, making HRES well suited for both off-grid rural electrification and grid-connected power supply. Overall, diversifying energy sources through hybrid systems improves energy stability by 20%, ensuring more reliable power delivery and reducing dependence on fossil fuel-based backup systems.

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