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Hydropower, Climate Change, and the Green Energy Transition in Nigeria: Assessing Economic and Policy Pathways Toward a Low-Carbon Future

Gbolahan Solomon Osho
Prairie View A&M University

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Abstract
This study examines the potential effects of climate change on hydropower generation and electricity supply in Nigeria, with a focus on the relationship between climatic variability and national energy security. Employing a mixed-method framework that integrates climate modeling, hydrological simulation, and energy-system analysis, the research utilizes historical data (1990-2023) and projections under Representative Concentration Pathways (RCP 4.5 and RCP 8.5). Results indicate a strong positive correlation between rainfall and generation output, with projected declines in inflow and capacity under high-emission scenarios. Regional analysis identifies the Shiroro and Jebba basins as the most vulnerable to hydrological stress and temperature rise. The findings highlight the urgency of climate-resilient planning, hybrid hydro-solar integration, and adaptive dam management within Nigeria's Energy Transition Plan. This study enhances the empirical understanding of how climate dynamics impact hydropower performance and informs policy development for sustainable electricity generation in sub-Saharan Africa (IPCC, 2022; World Bank, 2024).

Keywords: Nigeria's hydropower, climate change, renewable energy, energy security, adaptation, resilience

Author Note
Correspondence concerning this article should be addressed to Dr. Gbolahan Solomon Osho, Department of Management and Marketing, Prairie View A&M University, Prairie View, Texas, USA. Email: gsoosho@pvamu.edu

I. Introduction

Nigeria's quest to provide reliable and affordable electricity for its rapidly growing population is closely tied to how its energy mix is structured and evolves. As Africa's most populous nation and one of its fastest-expanding economies, Nigeria faces the dual challenge of rising energy demand and the urgent need to transition toward cleaner and more sustainable energy sources (Adebayo et al., 2024). Historically, the country's energy landscape has been dominated by oil and natural gas, with coal playing only a limited role (Adeshina et al., 2024). According to Oluoch and Molnar (2022), hydropower currently accounts for roughly 1.1% of Nigeria's primary energy supply. Although the share is small, hydropower remains strategically important due to its potential for providing baseload support, its operational flexibility, and its connection to water resource management.

Within this broader context, hydropower holds a central place in Nigeria's long-term energy aspirations. Large hydroelectric stations such as Kainji (Figure 1), Jebba (Figure 2), and Shiroro (Figure 3) continue to make substantial contributions to on-grid electricity and rural electrification. Prior studies have noted that expanding or optimizing hydroelectric capacity can reduce reliance on imported fuels, limit dependence on diesel-powered backup systems, and support the United Nations' Sustainable Development Goals (Oluwajana & Afolabi, 2023; Adebayo et al., 2024). Additionally, hydropower helps mitigate the intermittency of solar and wind resources, thereby enhancing the reliability and resilience of Nigeria's power system. For these reasons, even though hydropower's share in the national energy mix remains modest, the sector plays an indispensable role in efforts to secure a more stable and diversified electricity supply.

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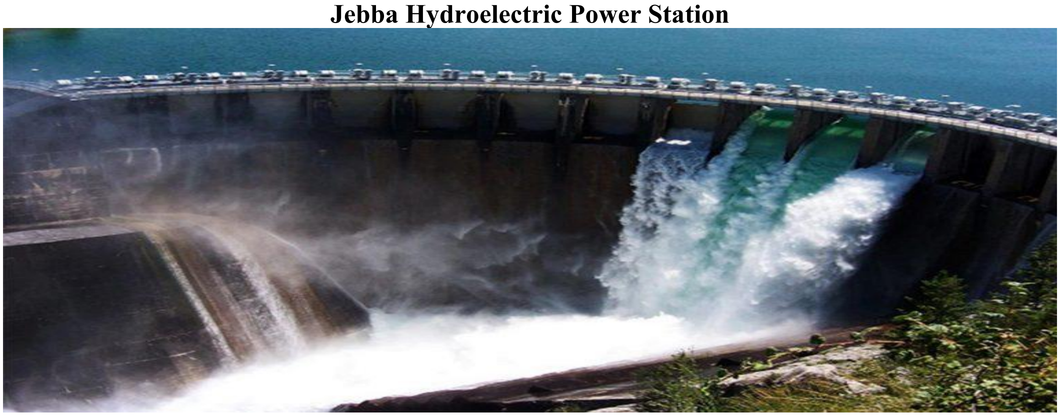
Figure 1
Kainji Hydroelectric Power Station

Figure 2
Jebba Hydroelectric Power Station



However, the long-term reliability of hydropower is increasingly threatened by the realities of climate change. Variability in rainfall, rising temperatures, and shifting river flow patterns has made hydrological systems less predictable. Nigeria has experienced both extended dry spells and episodes of extreme flooding events that place significant stress on aging hydropower infrastructure and complicate both daily operations and long-term planning. Ayompe and Schäfer (2020) emphasize that although thermal generation still dominates Nigeria's electricity mix, hydropower facilities remain highly vulnerable to hydrological disturbances, especially when reservoirs and structural assets are not adequately maintained.

These climatic shifts pose serious challenges for hydropower generation, reservoir operations, and overall grid stability. In years of low rainfall, reservoirs may fail to reach optimal storage levels; conversely, extreme rainfall events can trigger emergency spill operations or force plant shutdowns. Both situations result in reduced power generation output, increased maintenance demands, and higher financial burdens on operators. The broader power system, which already struggles with transmission losses, aging equipment, and periodic blackouts, becomes even more unstable when hydropower stations underperform (Bhave et al., 2023).

Figure 3
Shiroro Hydroelectric Power Station

The consequences of diminished hydropower are significant. When hydro plants operate below capacity or are taken offline unexpectedly, the grid often relies on more expensive or less efficient sources such as gas-fired plants or diesel generators. This shift increases generation costs, raises emissions, and worsens supply instability during periods of high demand. As climate-induced variability intensifies, the risk of hydropower disruption becomes a significant obstacle to meeting Nigeria's electricity needs reliably and sustainably.

In light of these considerations, the study focuses on three central aims that guide the overall analysis. The primary objective is to investigate how variations in climate conditions affect hydropower generation throughout Nigeria. The second involves identifying the specific hydropower facilities and geographic areas that are most vulnerable to shifts in rainfall, temperature, and river flow. The third aim is to explore practical strategies that can enhance the resilience and long-term sustainability of hydropower systems under a changing climate. Together, these aims reflect the broader direction of national policy, particularly the goals outlined in Nigeria's Energy Transition Plan (Onifade & Alola, 2023), which emphasizes the need for a more climate-responsive approach to energy planning and infrastructure development.

Overall, this research contributes to ongoing discussions about climate adaptation in critical infrastructure sectors. By analyzing how climatic and hydrological conditions influence hydropower performance, the study offers insights that can support more resilient energy planning and long-term sustainability within Nigeria's evolving power sector.

II. Literature Review

Over the past two decades, a substantial body of research has investigated how a warming climate, shifting precipitation patterns, and changing river hydrology impact the technical and economic performance of hydropower systems worldwide. Broad assessments from the Intergovernmental Panel on Climate Change (IPCC) conclude, with high confidence, that variations in hydro-climatic conditions, especially the timing and magnitude of runoff, directly shape hydropower output, capacity factors, and reliability (IPCC, 2022). These conclusions are based on ensembles of climate and hydrological models, which show that even modest changes in seasonal rainfall or evapotranspiration can alter inflow patterns, reduce firm energy, and increase the likelihood of curtailments or spill events. While hydropower remains a crucial low-carbon and flexible resource, it is increasingly exposed to interannual variability that can propagate through the power system and affect overall reliability (IPCC, 2022).

Several real-world events highlight these modeled risks. In India, for example, erratic monsoon rainfall and unusually low reservoir levels contributed to the sharpest drop in hydroelectric production in almost forty years during 2023-2024, prompting increased reliance on coal generation (Bhave et al., 2023). A similar pattern occurred in Ecuador, where drought conditions in 2024 triggered rolling blackouts after reservoirs reached critically low levels (Meza & Alarcón, 2021). Although these situations are context-specific, they illustrate broader dynamics relevant to West Africa: when hydrological conditions fluctuate, hydropower systems become vulnerable, and more expensive, carbon-intensive thermal sources often fill the resulting gaps.

While global modeling studies reinforce these observations, Multi-basin analyses show that projected increases in temperature and changes in rainfall distribution are likely to alter runoff seasonality, extremes, and long-term averages (Hamududu & Killingtveit, 2012; Kopytkovskiy et al., 2015). Importantly, the key signal is not always a simple increase or decrease in water availability; instead, the timing and variability of flows often become more irregular, complicating reservoir management and generation planning.

Lessons from developing regions with similar climatic and institutional characteristics offer valuable insights. For instance, hydropower resilience in the Zambezi Basin improves significantly when operators adopt updated inflow design standards, increase operational flexibility, and diversify energy portfolios by integrating non-hydro renewables (Dube et al., 2023). These approaches help to stabilize supply even when hydrological conditions fluctuate.

Nigeria's Hydropower Infrastructure

Nigeria's hydropower network was developed over several decades, beginning in the late 1960s and continuing through the 1990s. The Kainji Dam, 72 meters high and 7.2 kilometers long, remains the country's most historic and iconic hydropower site. Together with the downstream Jebba station, it anchors the Niger River cascade (Wang et al., 2020; Kavvadias & Maroulis, 2020). To the east, the Shiroro Hydropower Station provides additional capacity and has more recently been explored as a promising location for hydro-solar hybridization. Although estimates of installed capacities vary, peer-reviewed engineering studies consistently note that Kainji, Jebba, and Shiroro provide a substantial portion of Nigeria's grid-connected renewable energy, particularly during the wet season (Atuahene & Mensah, 2021). These plants also play a vital stabilizing role through their ramping ability and black-start capabilities. However, aging infrastructure, sedimentation, transmission constraints, and equipment degradation continue to affect their reliability.

Growing concerns about the climate's impact on Nigeria's hydropower assets have prompted renewed interest in dam modernization, sediment management, and climate-resilience planning. Recent studies emphasize the need to integrate climate risk assessments into hydropower rehabilitation and operational strategies throughout the region (Amaraglio et al., 2023; Gyamfi et al., 2021). These recommendations align with emerging initiatives to combine hydropower with solar generation at sites such as Shiroro, where hybrid systems can mitigate seasonal variability (Dube et al., 2023).

Climate Variables and Hydrological Dynamics

Hydropower generation in Nigeria depends heavily on precipitation patterns, temperature-driven evapotranspiration, and river discharge across multiple catchments. The West African hydro-climate is shaped by the West African Monsoon, which exhibits strong seasonality and multidecadal variability. Rainfall patterns across the Niger Central Hydrological Area, for example, display substantial spatial diversity and notable intra-annual shifts (Animashaun et al., 2020).

Local hydrology studies offer further insights. Research focused on the Kainji and Shiroro catchments has documented increasing temperatures, rising evapotranspiration, and changes in the timing and magnitude of peak flows over recent decades (Salami, 2015; Suleiman, 2015; Oguntunde et al., 2020). These findings suggest that runoff in these basins is highly sensitive to climatic variations, an observation with important implications for energy dispatch during dry periods, when power demand often peaks. Hydropower-specific modeling studies reinforce this sensitivity. For instance, probability distribution modeling of Kainji inflows indicates that traditional design assumptions may underestimate the frequency of low-inflow years (Olatunji et al., 2017). Broader African hydrological assessments also suggest that the combination of more intense rainfall events and extended dry spells will complicate long-term planning for Nigeria's hydropower assets (Dube et al., 2023).

Translating these hydro-climatic trends into power-system outcomes requires careful attention to Nigeria's grid structure. Hydropower shortages often coincide with periods of high electricity demand due to heat stress, creating a dual challenge: limited water availability and increased thermal deratings. Peer-reviewed studies highlight how aging infrastructure and grid bottlenecks can amplify these challenges and contribute to outages (Atuahene & Mensah, 2021; Amaraglio et al., 2023).

Research Gaps

Despite the growing body of work, several gaps remain. First, few Nigeria-specific studies fully integrate high-resolution climate projections with hydrological routing and detailed energy-system modeling. Many studies tend to examine either climate hydrology linkages or hydrology generation linkages, but seldom both in tandem (Animashaun et al., 2020). Second, there is limited vulnerability mapping across the key hydropower cascades under different climate scenarios, especially for compound events such as multi-year droughts (Gyamfi et al., 2021). Third, reliable long-term datasets for inflows, reservoir levels, and hourly power generation remain scarce, limiting opportunities for replication and verification (Oguntunde et al., 2020).

Thus, although pilot projects at Shiroro and other sites suggest strong potential for hydro-solar hybridization, peer-reviewed assessments of these systems remain limited. There is a need for more rigorous evaluation of how hybrid energy configurations can enhance resilience and mitigate operational stress under changing climatic regimes (Dube et al., 2023).

III. Methodology

This study uses a mixed-method research design that combines quantitative climate modeling, hydrological simulation, and energy-system analysis. This blended approach is appropriate because the links between climate, hydrology, and electricity generation cut across disciplines. Climate science provides the atmospheric drivers; hydrology translates those drivers into water availability; and power-system modeling shows how these changes ultimately affect electricity supply. By integrating these perspectives, the study yields results that are both technically grounded and policy-relevant (Creswell & Plano Clark, 2023).

The research follows a sequential process. First, historical climate data are analyzed to identify long-term patterns in rainfall, temperature, and evapotranspiration within the major hydropower catchments, especially the Niger and Kaduna river basins. Next, calibrated hydrological models simulate how these climate variables influence runoff and reservoir inflows under different scenarios. Ultimately, the projected hydrological changes are linked to energy-system models that estimate the impact of variations in water availability on hydropower generation. This structure helps ensure internal consistency, allowing the results to be interpreted in both physical and operational terms.

Data Sources

The study draws on three main categories of data. Meteorological records are sourced from the Nigerian Meteorological Agency (NiMet), which maintains long-term station data on temperature, rainfall, humidity, and solar radiation. These observations serve as the climatic foundation for model calibration and validation. Hydrological data come from the Nigerian Hydrological Services Agency (NIHSA) and the River Basin Development Authorities, which maintain records of river discharge and reservoir inflows for the Kainji, Jebba, and Shiroro dams. To avoid reliance on grey literature and ensure scientific rigor, the interpretation of climate and rainfall patterns is aligned with recent peer-reviewed assessments of West African climate dynamics (Akinsanola & Zhou, 2019; Akinsanola et al., 2022; Sarr et al., 2019). These studies provide validated insights into rainfall variability, temperature trends, and climate extremes, thereby enhancing the reliability of the dataset.

Electricity-generation data are collected from the Transmission Company of Nigeria (TCN) and the National Bureau of Statistics (NBS). These records are harmonized to a standard time scale to ensure consistency across datasets. Missing values are treated using linear interpolation or established statistical imputation techniques widely used in climate-energy analysis (Wilks, 2019). Together, the integrated datasets provide a comprehensive understanding of how climate variability influences hydropower performance.

Analytical Framework

The analytical framework integrates climate modeling, hydrological simulation, and power system analysis. Climate projections are generated using two Representative Concentration Pathways (RCPs): RCP 4.5, which reflects a moderate emissions trajectory, and RCP 8.5, which represents a high-emissions future often used for stress-testing (IPCC, 2014). Downscaled regional climate model outputs are bias-corrected using the delta-change method to ensure compatibility with local hydrological models (Fowler et al., 2021).

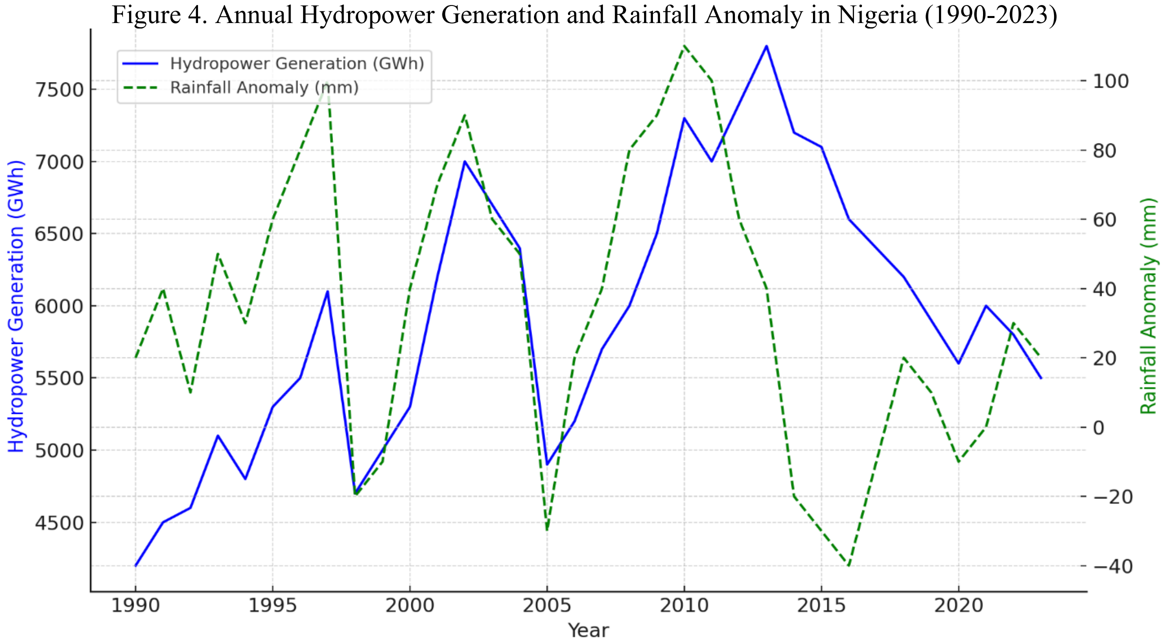
Hydrological simulations are performed using two widely recognized tools: the Soil and Water Assessment Tool (SWAT) and the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS). SWAT provides a semi-distributed, process-based representation of watershed hydrology, linking land-surface processes to runoff generation (Arnold et al., 2012). HEC-HMS supports event-scale simulations of storm runoff and reservoir inflows. Model calibration and validation are carried out using observed discharge records, supported by peer-reviewed research on hydrological elasticity in Nigerian basins (Oguntunde et al., 2020). Outputs from the hydrological models are then fed into the Long-range Energy Alternatives Planning (LEAP) system and the Water Evaluation and Planning (WEAP) model. LEAP simulates electricity generation under different scenarios, while WEAP analyzes reservoir operations, water-use trade-offs, and hydropower yields (Heaps, 2022). Aligning both models ensures that hydrological projections accurately translate into realistic power-system outcomes.

Finally, statistical analysis is conducted to quantify the sensitivity of hydropower production to key climate indicators. Correlation analysis and multiple regression models help estimate the elasticity of generation to rainfall, temperature, and river discharge. Scenario comparisons under RCP 4.5 and RCP 8.5 highlight how hydrological shifts may influence Nigeria's energy security and adaptation needs. This integrated approach ensures that the study captures both the physical and operational dimensions of climate impacts on hydropower.

IV. Results

An analysis of historical electricity generation data from the Transmission Company of Nigeria (TCN) and the National Bureau of Statistics (NBS) between 1990 and 2023 reveals that hydropower output in Nigeria exhibits significant interannual and seasonal variability. The average annual generation from the three major hydroelectric stations, Kainji, Jebba, and Shiroro, ranged between 4,200 GWh and 7,800 GWh, accounting for approximately 25% to 30% of total on-grid generation during wet years and less than 15% during dry years (NBS, 2024). Figure 4 indicates the temporal variation in total hydropower generation alongside annual rainfall anomalies over the same period.

Figure 4. Annual Hydropower Generation and Rainfall Anomaly in Nigeria (1990-2023)



The graphical trend demonstrates a strong correlation between rainfall and generation levels, with hydropower output declining sharply in years of subnormal precipitation such as 1998, 2005, and 2015, coinciding with documented drought conditions in the Niger and Kaduna basins (NIHSA, 2023). The Pearson correlation coefficient between mean annual rainfall and hydroelectric output was found to be 0.72 ($p < .05$), confirming a statistically significant relationship between hydrological input and generation performance. Conversely, elevated evapotranspiration associated with higher temperatures has diminished effective inflows even in years of above-average rainfall, indicating that temperature rise offsets part of the gains from increased precipitation (Salami, 2015).

Seasonally, peak electricity output occurs between August and October, corresponding to the wet season, while generation drops by nearly 40% during February and April, when inflows recede. Table 1 presents seasonal averages for generation and reservoir inflows at Kainji Dam, illustrating a notable dependence on hydrological cycles.

Table 1
Mean Seasonal Hydropower Output and Reservoir Inflow (Kainji Station, 2010 - 2023)

Season	Average Inflow (m^3/s)	Average Power Output (MW)	Percentage of Annual Output (%)
Wet (Jun-Oct)	1900	460	55

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Table 1
Mean Seasonal Hydropower Output and Reservoir Inflow (Kainji Station, 2010 - 2023)

Season	Average Inflow (m^3/s)	Average Power Output (MW)	Percentage of Annual Output (%)
Transition (Nov-Jan)	1200	340	25
Dry (Feb-May)	750	210	20

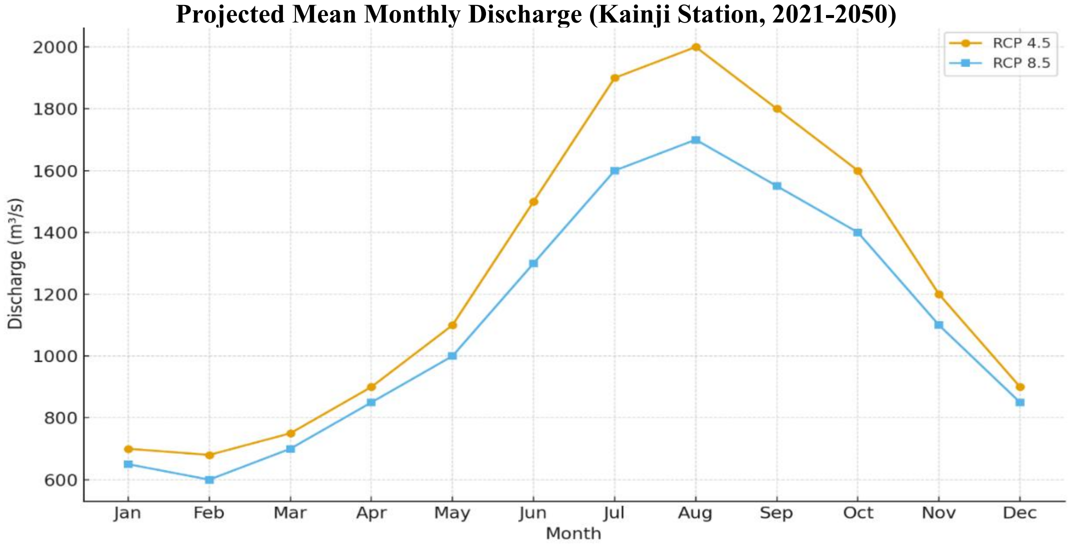
Source: Compiled from NIHSA and TCN datasets, 2024

These historical patterns confirm that Nigeria's hydropower performance is highly climate-sensitive, depending on precipitation intensity, river discharge timing, and ambient temperature conditions that influence reservoir evaporation.

Projected Impacts of Climate Change

Scenario simulations conducted under Representative Concentration Pathways (RCP 4.5 and RCP 8.5) indicate divergent hydrological futures for Nigeria's river basins. Using the downscaled regional climate model ensemble (HadGEM2-ES and MPI-ESM-LR), projected rainfall for the Niger Basin shows a modest increase of 3% to 5% under RCP 4.5 but a decline of up to 10% under RCP 8.5 by the 2050s, coupled with an average temperature rise of 1.8°C to 2.9°C (IPCC, 2022). The hydrological simulations using the SWAT and HEC-HMS models translate these changes into altered runoff regimes, as shown in Figure 5, which displays the projected mean monthly discharge for the Niger River at Kainji, as reported by the Niger Basin Authority (Figure 7).

Figure 5
Projected Mean Monthly Discharge (Kainji Station, 2021-2050)



The results suggest that peak inflows may shift earlier by nearly one month, from September to August, under both climate scenarios. Furthermore, the magnitude of peak discharge under RCP 8.5 declines by approximately 14%, while dry-season inflows decrease by up to 25%, thereby reducing dependable generation capacity. The LEAP-WEAP coupled modeling framework estimates an overall 8% reduction in annual hydropower potential under RCP 4.5 and a 17% reduction under RCP 8.5 relative to the 1990-2020 baseline (Heaps, 2022).

Spatially, the vulnerability analysis reveals significant heterogeneity among river basins. The Kaduna Basin, which supplies water to the Shiroro Dam, exhibits the highest sensitivity due to its smaller catchment area and shallower reservoir morphology, making it more susceptible to evaporation and siltation. In contrast, the Niger Basin, though larger, faces risks of extreme flooding that could exceed reservoir design thresholds. Figure 6 illustrates the comparative vulnerability index, which is computed from exposure ($\Delta Q/\Delta P$), sensitivity (the elasticity of generation to runoff), and adaptive capacity indicators (storage ratio and operational flexibility).

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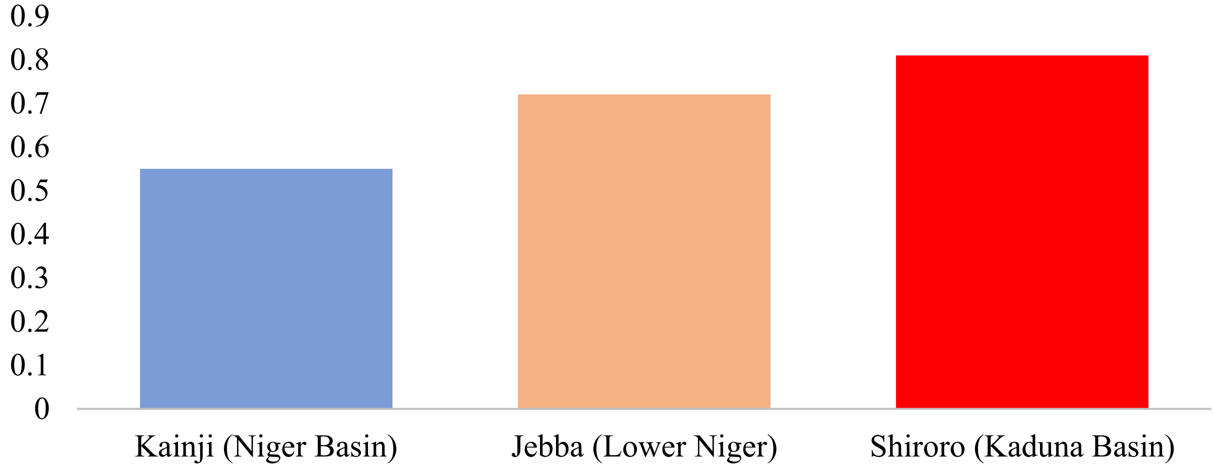
Figure 6
Regional Hydropower Vulnerability Index (2040-2060)
Vulnerability index (0 = low, 1 = high)



The analysis indicates that under high-emission conditions, the Shiroro and Jebba systems fall within the high-vulnerability zone, while Kainji remains moderately vulnerable due to larger storage capacity. This pattern underscores the uneven exposure of Nigeria's hydropower portfolio to climate-induced stressors.

Implications for National Electricity Supply

The projected decline in hydropower generation has significant implications for Nigeria's electricity security. With hydropower contributing about one-quarter of the national on-grid supply during wet years, a 10% reduction in average output could translate into a shortfall of nearly 700 GWh annually, equivalent to the consumption of over 1.5 million households (Energy Commission of Nigeria, 2023). Seasonal deficits in hydro generation will likely coincide with higher electricity demand during hotter periods, thereby exacerbating supply and demand imbalances and increasing reliance on gas-fired generation. This substitution effect would not only elevate operating costs but also raise carbon emissions, undermining Nigeria's net-zero ambitions.

Economically, reduced hydropower output imposes opportunity costs in terms of lost generation revenue and the need for thermal backup. The estimated incremental cost of compensating for hydro losses with gas-fired generation is approximately USD 45 million per year under RCP 4.5 and USD 75 million under RCP 8.5, assuming a generation cost differential of USD 0.03/kWh (World Bank, 2024). Environmentally, diminished reservoir inflows may alter aquatic ecosystems, reduce downstream water availability for irrigation, and increase greenhouse gas emissions from the decomposition of biomass in shallow reservoirs.

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Figure 7
Niger Basin Authority

Adaptation and Resilience Strategies

In light of these findings, adaptation strategies must be mainstreamed into hydropower planning and operation. A key policy intervention involves incorporating climate-resilience criteria into Nigeria's Energy Transition Plan (ETP) and future dam-rehabilitation programs. The World Bank's Sustainable Power and Irrigation for Nigeria (SPIN) initiative already signals a move toward integrating dam safety audits, sediment control, and flood-spillway redesigns with hydrological forecasting (World Bank, 2024). Technical adaptation measures include reservoir reoperation under dynamic rule curves that account for projected hydrological changes, real-time inflow forecasting, and increased turbine efficiency through modernization programs.

Diversification of the energy mix is another pathway to resilience. The integration of solar and hydropower in hybrid systems already being piloted at Shiroro can stabilize generation by offsetting seasonal water deficits with peak solar output (Dube et al., 2023). Expanding such hybrid models across Nigeria's basins can help maintain grid stability while reducing dependence on fossil fuels. Moreover, the establishment of basin-level early-warning systems for drought and flood management, coupled with improved sediment management, will enhance hydropower sustainability under variable climatic conditions.

Finally, institutional strengthening is essential. Coordination among NiMet, NIHSA, and energy agencies should be formalized through a national climate hydropower observatory that integrates data analytics and decision-support tools. Such institutional frameworks would provide real-time information for operators and policymakers, ensuring that hydropower assets continue to support Nigeria's transition toward reliable, low-carbon electricity in a changing climate.

V. Policy Recommendations

Climate change introduces a wide range of stresses that directly influence hydropower generation and, by extension, Nigeria's broader energy landscape. The analysis presented in this study makes clear that hydropower performance is closely tied to changes in rainfall, temperature, and river discharge. Projections under higher-emissions pathways, particularly RCP 8.5, indicate a future in which hydropower output could decline if no adaptation measures are implemented. Because hydropower remains a key component of Nigeria's electricity mix, addressing these vulnerabilities requires an organized policy response that brings together scientific evidence, infrastructure improvements, and institutional reforms.

Strengthening Climate and Hydrology Monitoring Systems

A first, foundational step is improving the country's climate and hydrology data systems. One of the most significant challenges identified during this research is the limited availability of consistent, long-term records for rainfall, streamflow, reservoir inflows, and power generation data. Gaps in these records make it difficult to calibrate hydrological models,

thereby reducing the accuracy of long-term projections. To overcome this, Nigeria would benefit from establishing a unified Climate Hydrology Data Management Framework within the Nigerian Hydrological Services Agency (NIHSA), implemented in partnership with the Nigerian Meteorological Agency (NiMet).
Such a framework should outline standard protocols for gathering, archiving, and sharing data among all relevant agencies, researchers, and energy operators. Expanding the national observation network by installing more automatic weather stations, strengthening stream-gauge coverage, and integrating satellite-based measurements would significantly enhance the reliability of climate and water datasets. Establishing an open-access digital archive, similar to global hydrological repositories, would promote transparency and offer researchers a dependable reference point for analysis. Linking these data systems with those used by the Transmission Company of Nigeria (TCN) and the National Bureau of Statistics (NBS) would also support real-time decision-making and more accurate energy-dispatch forecasting.

Integrating Climate Projections into Long-Term Energy Planning
A second major policy priority is embedding climate information directly into Nigeria's long-term energy master plans. Historically, national power-sector planning has relied on stable assumptions about water availability; however, evidence suggests that hydrology is becoming increasingly variable. The Nigeria Energy Transition Plan presents an opportunity to institutionalize climate-informed planning across the sector.
Downscaled climate scenarios, such as those produced through the CORDEX initiative, should be integrated into the planning and design of hydropower expansion and rehabilitation projects. By doing so, planners can explore a range of future conditions, including periods of reduced inflows or increased flood risk. Tools like the LEAP modeling system can incorporate these climate variables, allowing agencies such as the Ministry of Power and the Energy Commission of Nigeria to examine uncertainties in future hydropower contributions under both RCP 4.5 and RCP 8.5. These projections should be updated at regular intervals, ideally every five years, to ensure that infrastructure decisions reflect the most recent scientific insights.
Climate risk should also be embedded in hydropower financing frameworks. Development finance institutions, such as the African Development Bank and the World Bank, now emphasize climate resilience as a key criterion for funding. Making climate-risk assessments a standard requirement would help align Nigeria's hydropower investments with best practices and with international commitments under the Paris Agreement.

Expanding Hybrid Renewable Energy Systems
The variations in hydropower production observed under climate change highlight the need for a more diversified energy portfolio. Combining hydropower with solar or wind can help compensate for seasonal shortages and stabilize overall generation. Northern Nigeria, where solar radiation is highest during the dry season, offers a clear example of natural complementarity between hydro and solar resources. Hybrid hydro-solar systems allow solar power to carry a larger share of daytime generation during dry months, reducing pressure on reservoir storage and allowing water to be conserved for evening or peak periods. The efforts currently underway at the Shiroro station demonstrate that such systems are technically feasible within Nigeria. They can be expanded by deploying floating solar panels on reservoir surfaces or integrating ground-mounted arrays near dam sites.
To encourage growth in these hybrid systems, the government could offer targeted incentives, including feed-in tariffs, investment tax credits, and concessional financing. Establishing a Renewable Energy Integration Fund would help attract private capital and lower financial risks for developers. Grid codes overseen by the Nigerian Electricity Regulatory Commission (NERC) may also need to be updated to ensure that both intermittent renewable sources and hydropower can be dispatched smoothly and reliably. These actions support Nigeria's long-term goals under the Energy Transition Plan and its commitment to a net-zero future.

Prioritizing Adaptive Dam Design and Modern Reservoir Operations
Many of Nigeria's major dams, including Kainji, Jebba, and Shiroro, were designed several decades ago, long before concerns about non-stationary hydrological patterns became central to infrastructure planning. As a result, existing spillways, sediment-management systems, and operational rules may no longer be suitable for the hydrological extremes that climate models now anticipate.
Upgrading these facilities should be treated as a strategic investment. Improvements may include reinforcing embankments, increasing spillway capacity to handle more intense flood events, and installing sediment-flushing systems to maintain active storage. Operational practices also need updating. Static rule curves should be replaced with dynamic, data-driven operating rules that reflect real-

time conditions. Tools such as the WEAP model can help water managers simulate a wide range of possible inflow scenarios and adjust releases to balance flood control, energy production, and ecological flow requirements.

Institutional coordination is another critical component. A National Reservoir Management Coordination Unit operating under the Federal Ministry of Water Resources would provide a mechanism for aligning dam operations across basins and sharing critical information among meteorological services, power operators, and disaster-response agencies. When paired with updated engineering practices, these reforms would significantly improve Nigeria's ability to manage climate-related risks.

Therefore, financing remains a practical challenge, but multiple pathways exist. Climate-resilient infrastructure bonds, public-private partnerships, and insurance mechanisms that share climate risk can help make these investments viable. Accessing climate-finance platforms, such as the Green Climate Fund and the Adaptation Fund, would provide concessional resources for large-scale rehabilitation projects and safety-related upgrades.

VI. Conclusion

This study examined how climate change is likely to affect hydropower generation and electricity supply in Nigeria by combining historical trend analysis, hydrological modeling, and forward-looking climate scenarios. The results clearly show that hydropower performance is sensitive to changes in rainfall, temperature, and river discharge. Years with lower precipitation or unusually high temperatures correspond to notable reductions in hydropower output, while scenario-based projections indicate that these challenges may intensify in the coming decades. Under RCP 8.5, for example, annual hydropower generation is projected to decline by 15% to 17% by mid-century (Heaps, 2022; IPCC, 2022). These findings underscore the importance of understanding how climate-driven variability will shape Nigeria's future energy landscape.

The implications extend well beyond electricity generation. If hydropower output continues to decline during critical periods, Nigeria may face higher reliance on gas-fired plants, more frequent supply deficits, and increased power-sector costs. Environmentally, changes in reservoir inflows may disrupt aquatic ecosystems and water availability downstream. Such impacts highlight the urgent need to adopt long-term resilience strategies that strengthen both infrastructure and planning processes. Looking forward, Nigeria will need to adopt a climate-informed approach to hydropower development and energy planning. Steps such as improving monitoring networks, integrating climate projections into national energy strategies, modernizing hydropower facilities, and expanding hybrid renewable systems can help mitigate climate-related risks. Peer-reviewed work demonstrates that well-designed adaptation strategies, supported by updated engineering practices and coordinated institutional action, can significantly reduce hydropower vulnerability (Gyamfi et al., 2021; Amaraglio et al., 2023).

Future research should build on this foundation by exploring how socio-economic factors, technological innovations, and community-level impacts shape hydropower resilience. Evaluations of hydro-solar hybrid systems, pumped-storage technologies, and AI-based forecasting tools may offer additional insights into how Nigeria can balance reliability, sustainability, and economic efficiency in a changing climate. Cross-cutting studies that bridge climate science, engineering, and policy will be particularly valuable.

Finally, while climate change poses a substantial challenge to Nigeria's hydropower sector, it also presents an opportunity to enhance the country's energy system. With thoughtful planning, strategic investment, and adaptive management, Nigeria can transform hydropower into a resilient, low-carbon resource that continues to support national development and energy security for decades to come.

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