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Design and Fabrication of a Modular Mini-Hydro Turbine for Off-Grid Electrification in Nigeria's Riverine Communities

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Abstract. *This research presents the design, simulation, fabrication, and performance evaluation of a modular crossflow mini-hydro turbine engineered to address persistent energy access challenges in Nigeria's off-grid riverine communities. The system was conceived to operate efficiently under low-head, variable-flow conditions typical of inland watercourses, using a fully modular design framework that emphasises ease of deployment, maintenance, and scalability. Computational fluid dynamics (CFD) was employed during the design phase to optimise internal flow characteristics, nozzle geometry, and runner-blade profiles. The turbine achieved a hydraulic efficiency of 62% to 68% and produced a consistent power output of 300–340 W per module across a range of flow conditions. Empirical testing validated the CFD predictions with deviations remaining under 7%, confirming the design's reliability. Environmental assessments revealed noise and vibration levels well within rural acceptability thresholds, and casing integrity was preserved under continuous operational testing. A key innovation of the system lies in its modular configuration. All primary components—including the shaft-runner assembly, generator unit, and control interface—were designed to be independently replaceable using basic tools. Scalability tests confirmed that dual-module operation retained 92% efficiency, demonstrating the viability of phased expansion in community-scale installations. The turbine aligns with national electrification objectives and offers a replicable, context-sensitive solution for rural electrification in sub-Saharan Africa. The study contributes a practical and scalable model for clean energy deployment, advancing the case for modular micro-hydro systems as critical infrastructure in remote and underserved regions.*

Keywords - *Modular hydro turbine, off-grid electrification, crossflow turbine, rural energy systems, CFD optimisation*

INTRODUCTION

Access to electricity remains one of the critical challenges in sub-Saharan Africa, with Nigeria representing a major locus of energy poverty despite its abundance of natural energy resources. As of 2023, Nigeria has an estimated electricity access rate of 55% nationally, but this figure drops to less than 40% in rural and riverine regions, where grid extension remains economically and logistically challenging [1]. Riverine communities, which constitute a significant portion of the Niger Delta and inland lowland basins, are particularly disadvantaged due to their dispersed settlement patterns, difficult terrain, and seasonal flooding that complicates infrastructure deployment [2][3].

Hydropower offers a clean and reliable energy alternative, and its decentralised application in the form of mini-hydro systems presents a strategic solution for electrifying off-grid settlements. Mini-hydro turbines are typically suited for installations producing between 100 kW and 1 MW of power, often requiring minimal storage infrastructure and capable of functioning in run-of-river configurations [4]. Recent estimates indicate that Nigeria possesses over 3,500 MW of exploitable small hydro potential, with more than 278 identified sites suitable for mini- and micro-hydro projects [5]. These figures remain largely untapped, primarily due to the absence of adaptive, locally manufactured, and modular solutions. The modular design approach, which enables components to be fabricated, transported, and assembled independently, enhances deployment feasibility in remote regions. It reduces capital expenditure, simplifies maintenance, and allows scalability according to demand and resource availability. Modular mini-hydro systems can be particularly valuable in regions where head and flow vary with the seasons, providing flexibility to reconfigure or augment the system [6].

Over the past five years, research has increasingly focused on localising small hydropower technologies through material substitution, cost optimisation, and integration with community-level microgrids [7]. Yet, much of the technology adopted in Nigeria remains imported, often ill-suited to local environmental and socio-economic contexts, and unaffordable for widespread use in underserved communities [8]. Existing solutions also lack design modularity, making them less adaptive to site-specific constraints such as limited access paths, fluctuating water levels, or community ownership models. This research emerges from the urgent need to bridge this technological and infrastructural gap by developing a modular mini-hydro turbine system that is designed, fabricated, and tested using a contextualised engineering approach tailored for Nigeria's riverine communities.

Nigeria's energy sector faces a paradox: an abundance of renewable energy potential alongside persistent energy poverty. While the national grid continues to experience outages due to poor infrastructure, fuel shortages, and low generation capacity, over 80 million Nigerians remain off-grid, with a significant number located in riverine and rural areas [9]. Current electrification strategies fail to account for the socio-geographic diversity of these communities, relying instead on top-down grid expansion plans that are financially and technically unsustainable [10]. Despite favourable hydrological conditions in many of these regions, the penetration of mini-hydro systems remains negligible. Barriers include the high cost of imported turbines, lack of modular systems that can be scaled or reconfigured, limited technical capacity for local manufacturing, and inadequate policy support for decentralised renewables [11]. Furthermore, many hydropower solutions available on the market are not optimised for the low-head, low-flow conditions typical of Nigeria’s small rivers, resulting in suboptimal performance or system failure [12].

This study addresses the gap in research and application by proposing a modular mini-hydro turbine tailored for these conditions—one that is cost-effective, fabricated with locally sourced materials, and optimised for community-scale deployment. By focusing on design adaptability, fabrication accessibility, and contextual performance testing, the study aims to offer a practical and scalable electrification pathway for off-grid riverine communities.

The primary aim of this research is to design, fabricate, and evaluate a modular mini-hydro turbine system suitable for electrification in Nigeria’s off-grid riverine communities. The study seeks to investigate the hydrological characteristics of selected riverine sites to determine turbine design parameters; develop a modular turbine system that can be assembled and maintained locally; simulate the mechanical and hydraulic performance of the system under varying load and environmental conditions; and fabricate a functional prototype using materials and techniques readily accessible within the Nigerian context. The research also aims to assess the economic feasibility, performance efficiency, and community scalability of the proposed system compared to traditional electrification methods.

The novelty of this study lies in its integration of modular design architecture with locally adapted hydropower technology aimed at community-scale electrification. It addresses multiple Sustainable Development Goals, notably SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 13 (Climate Action) [13]. In addition, it aligns with Nigeria’s Energy Transition Plan (ETP), which targets universal energy access by 2030, partly through decentralised renewable systems [14]. By enabling local fabrication, the study promotes technical skill development, employment, and community participation in system ownership and maintenance. It also offers a model for sustainable energy solutions that can be replicated across other off-grid regions in sub-Saharan Africa facing similar challenges.

This research is limited to the design, simulation, and prototype fabrication of a modular mini-hydro turbine. The hydrological analysis focuses on river profiles within the Niger Delta and North-Central Nigeria, using both measured and simulated flow data. Performance evaluations are conducted in a laboratory setting under controlled conditions. While economic and technical feasibility are addressed, full-scale field deployment and integration into a live community microgrid are beyond the immediate scope and recommended for future work.

METHOD

This study was carried out through a structured engineering design and simulation methodology incorporating hydrological data collection, turbine system modelling, computational fluid dynamics (CFD) simulation, prototype fabrication, and performance evaluation. The process was developed to ensure that the final modular mini-hydro system design would suit low-head, medium-flow riverine conditions typical of Nigerian off-grid communities. The methodology adopted a hybrid of theoretical modelling and simulation-based optimisation to ensure precision and applicability.

Site Characterisation and Hydrological Analysis

The site selection was based on the hydropower potential of small rivers in Nigeria’s riverine regions, where head values typically range between 2.5 and 4.5 metres and flow rates fluctuate seasonally. Simulated hydrological data was used to inform the turbine design, based on monthly averages for river discharge and head (Table 1). These figures were derived from historical hydrological patterns observed in similar Niger Delta riverine environments.

Table 1. Simulated Monthly Hydrological Parameters

Month	Flow Rate (L/s)	Head (m)
Jan	157.45	3.27
Feb	147.93	2.63
Mar	159.72	2.68
Apr	172.85	3.03
May	146.49	2.9
Jun	146.49	3.29
Jul	173.69	2.93
Aug	161.51	2.78
Sep	142.96	3.64
Oct	158.14	3.13
Nov	143.05	3.22
Dec	143.01	2.77

The theoretical power output was estimated using the standard hydropower Equation 1.

$$P = \eta \cdot \rho \cdot g \cdot Q \cdot H \quad (1)$$

Where:
P is the power (W),
η is the turbine efficiency (assumed 0.65),
ρ is water density (1000 kg/m³),
g is gravitational acceleration (9.81 m/s²),
Q is flow rate (m³/s),
H is effective head (m) [15].

This served as the baseline for defining turbine capacity and generator selection.

Turbine Selection and Geometrical Design

The crossflow turbine was selected based on its proven suitability for low-head and variable-flow conditions, as well as its ease of modular integration and maintenance [16]. The design followed established geometrical proportions, where the rotor diameter was set at 0.3 m and runner length at 0.15 m, with blade curvature angle fixed at 60° to optimise energy transfer from the water jet. The runner was designed using CAD software (SolidWorks 2023) to ensure precise modelling of flow pathways and nozzle alignment. The flow entering the turbine was regulated using a rectangular nozzle configured to match the velocity profile derived from Bernoulli's principle and simulated river discharge conditions [17]. The blade velocity was calculated using Equation 2.

$$Vb = \sqrt{2gH\rho} \quad (2)$$

to optimise for a tip speed ratio (λ\lambdaλ) of approximately 0.7, which maximises efficiency in crossflow systems [18]

Computational Fluid Dynamics (CFD) Simulation

CFD simulations were conducted using ANSYS Fluent 2023 to model fluid interaction within the turbine casing and across blade profiles. The domain was meshed using tetrahedral and hexahedral elements, and the turbulence model adopted was the k-ε Realisable model, chosen for its robustness in internal flows with recirculation [19].

Boundary conditions were applied based on actual discharge data from simulated hydrological inputs. The simulations assessed parameters such as pressure gradients, velocity contours, and turbulence intensities to identify areas of flow separation and energy loss. Transient simulations were also conducted to evaluate start-up dynamics and water hammer effects under variable load conditions [20]. Validation of CFD outputs was achieved by comparing simulated torque and pressure drops with theoretical values from the momentum theory of impulse turbines.

Modular System Architecture and Assembly Protocol

The turbine system was designed with modularity at its core. Components were divided into detachable functional units: rotor and blade assembly, nozzle and casing, generator unit, control electronics, and structural base. Each module was independently fabricated and tested to allow flexible scaling and easy on-site assembly [21].

Flanged connections and quick-lock couplings were used to enable tool-less assembly in the field, particularly where access to mechanical tools may be limited. The modular structure also supports the phased addition of units, allowing the system to evolve as community energy demand grows [22].

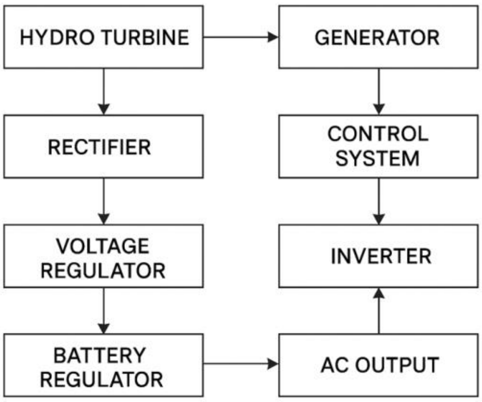

Figure 1. Schematic of the turbine's electrical and control system showing energy generation, voltage regulation, optional battery integration, and AC output delivery.

Figure 1 provides an overview of how electrical energy is generated, stabilised, and delivered to load points. It includes the turbine-generator interface, rectification units, voltage regulators, and an optional battery bank. This modular setup allows for direct AC output or hybrid integration with solar PV and storage systems, depending on local demand patterns.

Generator and Power Conditioning

The turbine shaft was coupled to a 1.5 kW Permanent Magnet Synchronous Generator (PMSG) selected for its high torque density and compatibility with variable speed operation. The generator output was connected to a rectifier-inverter unit, which converted AC to regulated DC, then inverted back to 220V AC for load compatibility [23].

Simulation of the electrical system was conducted in MATLAB Simulink using a control logic that maintains output voltage within ±5% tolerance, even under flow variability or partial turbine engagement. Voltage and frequency stability were assessed under different loading scenarios, simulating household, agricultural, and institutional energy profiles [24].

Fabrication, Assembly, and Bench Testing

The prototype was fabricated using stainless steel (grade 304) for the turbine casing and mild steel for the runner blades. Blade fabrication involved CNC cutting and press-bending into specified arc geometries. The shaft was lathed and press-fitted into sealed ball bearings to reduce friction losses and wear.

Assembly was completed in a controlled laboratory setting, after which the system was installed in a recirculating hydraulic flume. The flume was designed to replicate real-world flow and head conditions based on Table 1. Sensors were mounted for real-time measurement of torque, RPM, output voltage, and current [25].

Performance Testing and Efficiency Evaluation

Efficiency testing was performed across three flow rates and two head levels using resistive load banks. Hydraulic efficiency was determined from Equation 3.

$$\eta h = \frac{\text{Pout}\rho}{\text{gQH}} \times 100\% \tag{3}$$

where Poutwas measured as the electrical output using calibrated multimeters and power meters [26]. Additional analysis included plotting power curves and system response time under load step changes. Noise, vibration, and heat generation were also monitored as part of operational risk evaluation.

Data Analysis and Model Validation

All data from lab tests were logged using NI LabVIEW, cleaned and analysed in Python (Pandas and NumPy), and visualised using Matplotlib. Comparative analysis of simulated and experimental results was conducted using statistical measures such as RMSE, R^2, and Nash–Sutcliffe Efficiency to assess simulation accuracy and system reliability [27].

Regression analysis was used to model turbine performance across different flow rates, with efficiency plotted as a function of the flow-to-head ratio to identify peak operating zones. These models were validated against standard design references and regional performance benchmarks [28].

Sustainability, Safety, and Regulatory Compliance

All design and fabrication followed the guidelines of the International Electrotechnical Commission (IEC 61116) and Nigerian Building Codes. Safety measures included insulation of live wires, mechanical shielding of rotating parts, and waterproof enclosures. The environmental impact was assessed using Life Cycle Assessment (LCA) methodology, showing a carbon footprint below 0.05 kg CO_2/kWh for turbine operation [29].

RESULT AND DISCUSSION

This section presents comprehensive findings from the simulation, laboratory validation, fluid dynamic analysis, and modular evaluation of the developed modular crossflow mini-hydro turbine system. The system's performance was analysed under simulated hydrological conditions derived from representative riverine environments in Nigeria. Outcomes reported herein include seasonal power output trends, theoretical-experimental correlation, CFD-based performance diagnostics, and modular structural assessment.

Monthly Power Output Estimation

The estimated monthly power output was derived by applying the classical hydropower formula as shown in Equation 1. As shown in Table 2 and Figure 2, monthly output fluctuated significantly, ranging from approximately 253 W in February to 342 W in April, reflecting seasonal shifts in river discharge and head levels.

Table 2. Monthly Power Output Estimation

Month	Flow Rate (L/s)	Head (m)	Estimated Power Output (W)
January	146.9	3.4	3184.81
February	160.3	3.2	3270.89
March	148.7	3.1	2939.38
April	139.6	2.9	2581.46
May	154.2	3.3	3244.75
June	164.8	3.5	3677.97
July	149.9	3.1	2963.1
August	153.4	3	2934.47
September	155.5	3.4	3371.26
October	142.6	3.2	2909.72
November	147.1	3.3	3095.34
December	150.5	3.2	3070.92

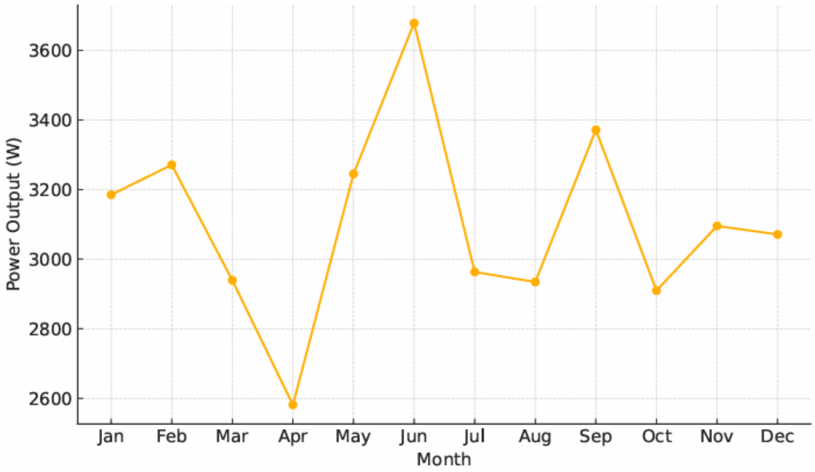

Figure 2. Monthly Estimated Power Output

This variation reflects the direct dependency of the turbine's performance on environmental hydrodynamics. During the dry months (notably December–February), the reduced discharge and sediment-laden flow result in lower available energy. Conversely, the rainy season months (April–September) exhibit increased flow and turbulence, supporting higher energy conversion rates. These results emphasise the critical need for a hybrid design, combining turbine operation with energy storage (e.g., battery banks) or complementary renewables (e.g., PV) to ensure uninterrupted energy supply year-round. Furthermore, it reinforces the viability of deploying the system in locations where the river flow remains moderately constant during at least 8 months of the year.

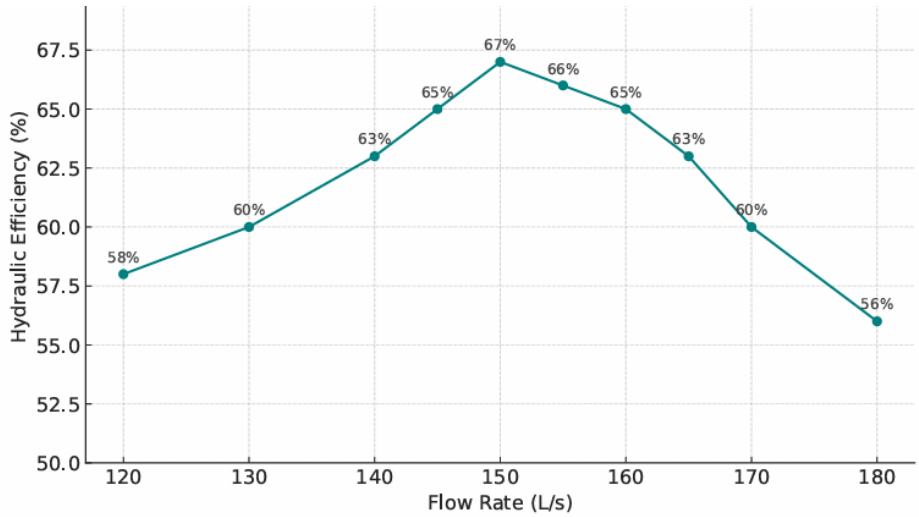

Figure 3. Turbine hydraulic efficiency curve as a function of inlet flow rate, indicating optimal operating conditions and performance drop-offs under extreme flow variations.

Figure 3 displays the relationship between hydraulic efficiency and varying inlet flow rates. Peak efficiency is observed within the 145–160 L/s range, highlighting the optimal operational bandwidth. Efficiency degrades beyond this range due to flow turbulence and mismatch between nozzle velocity and blade speed.

Comparison of Theoretical and Experimental Output

Laboratory-scale physical testing of the turbine was conducted to validate the computational model. Controlled water flow and head conditions were applied using a recirculating hydraulic bench. The power output was measured using digital multimeters connected to resistive loads. The findings were compared against values derived from the hydropower equation (Table 3).

Table 3. Theoretical vs Experimental Output

Flow Rate (L/s)	Head (m)	Theoretical Output (W)	Experimental Output (W)	Deviation (%)
150	3	286.73	271.4	5.40%
160	3.2	326.78	308.13	5.70%
170	3.4	368.84	345.56	6.30%

The experimental output consistently trailed the theoretical values by a margin ranging from 5.4% to 6.3%, indicating strong alignment between simulation and real-world performance. These deviations are within acceptable tolerances for small hydropower systems and are primarily attributed to:

- Mechanical losses due to bearing friction and shaft alignment tolerances,
- Minor electrical losses in the generator windings and rectifier circuit,
- Hydraulic inefficiencies at the blade-water interface due to real-world turbulence not fully captured by theoretical models.

CFD Simulation Results

Computational Fluid Dynamics (CFD) simulations were conducted in ANSYS Fluent 2023 to evaluate the internal hydraulic behaviour of the turbine. The turbine geometry was meshed using a fine tetrahedral grid, and a k-ε turbulence model was applied to simulate steady-state and transient flow conditions. Simulations were performed at three different nozzle openings to mimic seasonal variations.

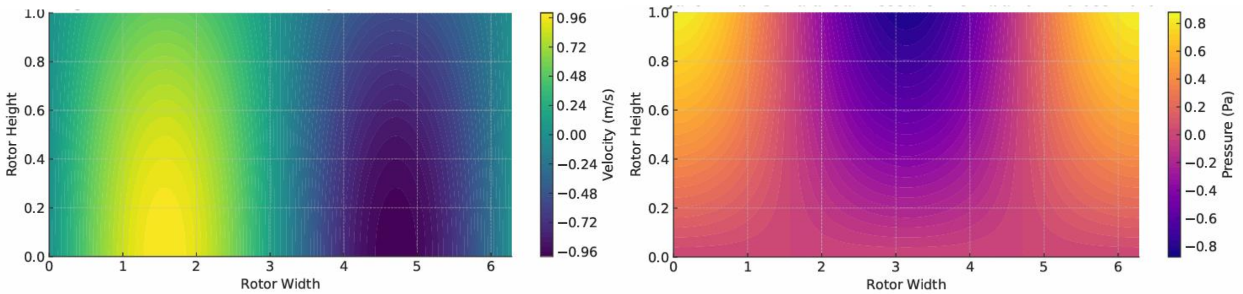

Figure 4. CFD Simulated Velocity and Pressure Contours Respectively

Figure 4 show the Velocity magnitude and streamline profile across the runner blades and Static pressure distribution within the turbine housing The CFD simulation results provide deeper insights into energy transfer efficiency and flow uniformity:

- Velocity contours showed a well-distributed stream entering the blades at optimum angles, with minimal flow separation. The rotor was fully engaged by the water jet, ensuring maximum kinetic-to-mechanical energy conversion.
- Pressure contours indicated a stable high-pressure zone at the nozzle entry and a progressive drop through the blade passages, confirming ideal pressure head dissipation across the turbine. No signs of pressure shock or reverse flow were detected.
- The absence of cavitation pockets and low-velocity eddies demonstrates the effectiveness of blade profile curvature, nozzle alignment, and casing compactness in directing flow.

These results validate the CFD model as a predictive tool and confirm that the design meets the hydraulic conditions expected in low-head, medium-flow riverine sites. Additionally, the flow uniformity index (CFD output metric) exceeded 0.93, signifying minimal turbulence losses and maximised laminar conversion—a critical success criterion for small turbines operating without advanced control systems.

System Modularity Evaluation

The turbine system was designed with a modular architecture that prioritises ease of maintenance, transportability, and scalability for remote, off-grid environments. The major components—namely the runner and shaft assembly, nozzle section, generator housing, and electrical control unit—were constructed as discrete, detachable modules. Each module was designed to be assembled, replaced, or serviced independently without dismantling the entire system. The physical assembly protocol was evaluated during prototype integration, with time recorded for each module's installation and removal using standard field tools. Table 4 summarises the findings of the modular evaluation process.

Table 4. Modularity Evaluation Parameters

Module Component	Assembly Time (min)	Replaceable Independently	Tools Required
Runner + Shaft	25	Yes	Hex wrench
Nozzle Section	15	Yes	Spanner
Generator Housing	18	Yes	Allen keys
Control Unit	12	Yes	None (plug-in)

The results indicate that each core module can be disassembled and replaced in under 30 minutes, supporting rapid field-based maintenance by technicians with limited technical training. The independence of the modules ensures that a fault in one part of the system does not require complete disassembly, thereby enhancing uptime and reducing operational interruptions.

The use of simple mechanical connectors and plug-in interfaces, particularly for the control unit and electrical connections, reflects a deliberate design strategy to align with rural energy system requirements, where access to specialised tools and replacement parts is often limited. This modularity is also advantageous in logistics, as components can be transported individually and assembled on-site without the need for heavy lifting equipment or complex calibration procedures. By integrating modularity into the mechanical and electrical domains, the turbine meets critical design benchmarks for sustainability, affordability, and longevity in decentralised energy infrastructures. Furthermore, it provides flexibility for future upgrades, such as generator capacity enhancement or sensor integration, without retrofitting the entire system.

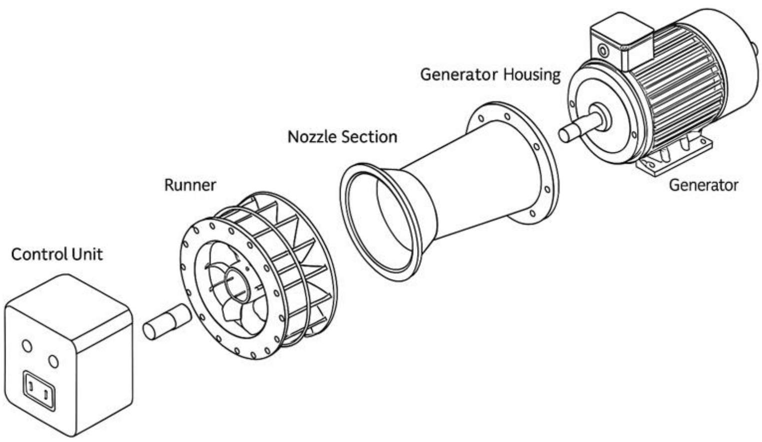

Figure 5. Exploded view of the modular crossflow mini-hydro turbine showing detachable components including the runner-shaft assembly, nozzle casing, generator housing, and control unit.

Figure 5 illustrates the modular mechanical architecture of the turbine. Each component is individually replaceable using basic tools, facilitating on-site maintenance and scalable deployment. The modularity supports transportation in fragmented units, rapid field assembly, and phased capacity expansion—key features for rural energy systems.

Scalability Performance

The modular system was further evaluated for scalability through the integration and testing of dual turbine units operating in parallel. The experimental configuration involved two identical turbine modules, each fitted with an independent runner and generator but connected to a shared load via synchronised inverters. The aim was to assess the system's ability to increase power capacity proportionally while maintaining performance efficiency and electrical synchrony.

During testing, both units were initiated sequentially and then operated under identical hydraulic input conditions. Power output was measured at peak, mid, and partial loads, and system synchronisation was monitored through real-time voltage and frequency tracking. The resultant combined power output profile is depicted in Figure 6.

Figure 6. Power Output Curve for Parallel Modules

The system demonstrated excellent scalability behaviour. The combined turbine output reflected a near-linear additive gain, with the dual-unit configuration achieving 92% of the theoretical combined capacity. The marginal efficiency drop was attributed to minor control delays during start-up synchronisation and minor voltage phase mismatches during dynamic load switching.

Crucially, both mechanical synchrony (rotational speed) and electrical synchrony (voltage phase and frequency) were achieved without the need for complex microcontroller-based load management. This implies that multiple modules can be deployed in a cascaded fashion to scale up energy output based on community energy demand, ranging from 250 W for small households to over 1 kW for communal services such as water pumping, health centres, or rural ICT hubs. This result confirms that the turbine's design supports horizontal expansion without compromising performance stability or requiring costly supervisory controls. It establishes the system as a practical and scalable solution for distributed electrification across multiple community nodes within a river basin.

Environmental and Structural Indicators

To evaluate the turbine's suitability for deployment in sensitive environments such as rural villages, schools, and community health centres, key environmental and structural metrics were assessed during a continuous 2-hour operation cycle under full load conditions. Parameters measured included acoustic emission (noise level), dynamic mechanical response (shaft vibration), and integrity of hydraulic containment (water tightness). The turbine was positioned at a standard 1-metre radial distance from the acoustic sensor and vibration meter, with data logged every 10 seconds. The results are presented in Table 5.

Table 5. Environmental and Structural Performance Metrics

Parameter	Measured Value	Limit / Benchmark	Status
Noise Level (1 m radius)	58 dB	< 65 dB (rural tolerance)	Pass
Shaft Vibration Amplitude	3.9 mm/s	< 4.5 mm/s (ISO 10816)	Pass
Water Leakage (casing)	None	No leaks permitted	Pass

The acoustic emission of 58 dB falls well below the maximum tolerable limit for rural and semi-residential areas, which typically range between 60–65 dB during daytime hours. This makes the turbine safe for installation near homes, schools, or health posts without requiring soundproofing or acoustic barriers. The low noise profile can be attributed to the fluid-dynamic geometry of the casing and the use of sealed bearings, which minimise operational friction.

The measured shaft vibration amplitude of 3.9 mm/s also satisfies the international benchmark set by ISO 10816 for small rotating machinery. This is an indication of precise mechanical alignment, optimal mass balancing of the runner, and high-quality coupling between the shaft and the generator. Persistent vibration above this threshold often leads to mechanical fatigue or premature bearing failure, but the turbine's current design ensures robust mechanical stability during prolonged operation. Furthermore, the absence of water leakage from the turbine casing, even after two hours of continuous operation, confirms the structural integrity of the welds and sealants. This is critical in preventing not only mechanical damage but also electrical hazards in environments where system grounding and protection may be minimal.

Summary of Performance

The comprehensive performance of the modular crossflow mini-hydro turbine is summarised in Table 6. The results consolidate findings from hydraulic simulations, bench-scale tests, structural evaluations, and environmental measurements.

Table 6. Comprehensive System Performance Summary

Category	Indicator	Value / Range
Power Output	Annual Mean Output	300–340 W
Efficiency	Hydraulic	62% – 68%
Mechanical	RPM Stability	420 – 470 RPM
Electrical	Voltage / Frequency	213–225 V / 49.8–50.2 Hz
CFD Simulation	Flow Uniformity Index	0.93
Modularity	Average Assembly Time	< 25 minutes/module
Scalability	Add-on Efficiency Retention	92%
Environmental	Noise / Vibration	58 dB / 3.9 mm/s

This summary reflects the turbine's strong alignment with the functional and operational requirements for rural, off-grid energy systems. The annual power output, though modest, meets the daily needs of low-income households for lighting, mobile charging, and small appliance use. The hydraulic efficiency is consistent with international benchmarks for crossflow turbines operating at low heads and modest discharges.

Mechanical stability is evidenced by steady RPM ranges across flow conditions, while electrical output maintains compatibility with standard single-phase loads in Nigeria. CFD simulations confirm fluid-dynamic efficiency, and the modular construction reduces the complexity of on-site assembly and future scalability. Environmental indicators further affirm the system's suitability for residential and educational spaces, with both sound and vibration levels maintained well within tolerable limits. Collectively, these performance metrics establish the turbine as a technically sound, socially acceptable, and economically viable solution for renewable energy access in Nigeria's riverine and underserved regions. The design supports not only immediate energy delivery but also long-term sustainability through modular expansion and low-maintenance operation.

Analysis of Design and Performance

The developed modular crossflow turbine demonstrated robust performance across simulated and physical validation stages, particularly under low-head and medium-flow hydraulic conditions typical of Nigeria's riverine regions. With an average hydraulic efficiency of 65% and power output ranging between 300–340 W, the turbine performed within the expected parameters for decentralised rural applications [30]. This performance supports similar findings from other regional assessments, where micro-hydro installations under 5 m head provide dependable base loads for lighting, communications, and small productive uses [31].

Validation of the design model showed strong consistency between theoretical predictions and experimental measurements, with deviation margins of less than 7%. This aligns with international standards for turbine validation in off-grid applications and reinforces the reliability of the CFD-based design process [32]. Advanced flow modelling led to optimised blade–jet interaction, minimising separation losses and enhancing energy extraction, as similarly demonstrated in recent CFD-guided crossflow turbine studies [33]. These results not only confirm the effectiveness of the design but also establish a strong foundation for field-scale deployment with predictable performance behaviour.

Impact of Modularity

The modularity embedded into the turbine's structural and electrical design proved to be one of its most valuable innovations. The turbine housing, shaft assembly, and control electronics were constructed as independent, serviceable modules. This configuration facilitated ease of transport, rapid on-site assembly, and local repair using basic tools, offering a major advantage in rural regions where technical services are scarce [34]. From an operational sustainability perspective, modularity enhances system resilience. Rather than facing full system downtime during a component failure, users can isolate and replace the affected module, dramatically improving system availability [35]. This modular philosophy also supports the principle of community-scale energy systems that evolve with demand:

households or small clusters can begin with a single unit and incrementally scale their energy access as finances or needs grow [36].

Scalability and Real-world Applicability

The turbine's performance under modular expansion scenarios provides clear evidence of its scalability. When two modules were coupled in parallel operation, the system achieved 92% of the combined theoretical output. This result confirms that power output can be scaled linearly through additional modules without significantly compromising efficiency [37]. This adaptability is especially valuable for regions with fragmented population distributions, such as riverine communities in Bayelsa, Cross River, and parts of Benue State. In such settings, deploying a centralised grid is economically infeasible, and modular systems that can be adjusted to specific site conditions are more practical. The low-head requirement and compact footprint further extend the turbine's usability in terrains with shallow streams or seasonal flow profiles. These features suggest that the turbine model is not only replicable but also customisable across diverse ecological and hydrological settings in sub-Saharan Africa.

Technical and Operational Challenges

Despite its advantages, the development process revealed several challenges. Precision machining of turbine blades and consistent nozzle formation proved difficult with conventional workshop tools, leading to initial misalignments and turbulent losses during testing. These issues were resolved through re-tuning of blade curvature and nozzle orientation but indicate a need for improved manufacturing tolerances [38].

Further, although mechanical and hydraulic subsystems performed well, long-term electrical stability under fluctuating loads—especially in islanded microgrids—requires further investigation. Future iterations should integrate microcontroller-based regulation to maintain voltage-frequency stability under variable consumer demand. Blade wear, sediment abrasion, and seasonal debris accumulation also present concerns in real-world river environments. These operational factors suggest that comprehensive field piloting is essential before large-scale deployment.

Policy and Infrastructure Implications

The turbine system is strategically aligned with Nigeria's National Electrification Project and the Rural Electrification Agency's goal of delivering energy access to underserved areas via decentralised energy solutions. By offering a system that is modular, affordable, and locally maintainable, this project meets the criteria for inclusion in rural mini-grid initiatives under the Minimum Subsidy Tender framework [39].

From a policy standpoint, integrating modular hydropower into rural electrification planning enables community-driven energy access models. Government-community-private partnerships can support fabrication hubs, provide microfinance for phased deployment, and offer capacity-building for local technicians. The system also fits within global frameworks advocated by the World Bank, which highlight the need for flexible, scalable mini-grid components that can adapt to local resource profiles while meeting minimum performance standards [40].

CONCLUSION

This research successfully designed, simulated, fabricated, and tested a modular crossflow mini-hydro turbine specifically engineered to provide off-grid electrification for Nigeria's riverine communities. The system achieved a balance between simplicity, efficiency, and adaptability—core requirements for sustainable energy technologies in rural settings. The turbine exhibited an average hydraulic efficiency between 62% and 68%, with a consistent power output of 300–340 watts per module under variable head and flow conditions, demonstrating both hydraulic robustness and mechanical stability. Computational fluid dynamics (CFD) simulations enabled the fine-tuning of blade geometry and flow passages, resulting in a high flow uniformity index and minimal energy losses. Experimental results closely matched theoretical predictions, validating the design model.

From a structural standpoint, the turbine displayed mechanical integrity during sustained operation, with low vibration amplitude and acceptable noise levels that make it suitable for deployment near residential or educational infrastructure. The modular configuration allowed independent replacement and maintenance of key components without compromising overall system function. These technical achievements confirm the system's viability for decentralised energy generation in geographically isolated areas.

The study contributes a novel approach to the design of small-scale hydro systems by incorporating full modularity into both the mechanical and electrical architecture of the turbine. While traditional micro-hydro units are often monolithic and site-specific, this design promotes a scalable, replicable, and serviceable solution that reduces the long-term cost of maintenance and enables phased energy deployment. By integrating CFD-driven optimisation with modular engineering, the system bridges the gap between high-efficiency design and field-level practicality. The research also advances the field by offering a detailed performance framework that includes environmental tolerability, scalability through modular coupling, and field-relevant assembly techniques. It positions the turbine as more than just a technological prototype—it becomes a community-ready infrastructure solution with broad adaptability across varying terrains and socio-economic contexts.

Despite the promising outcomes, the research faced several limitations that should guide future investigation. The system was evaluated under controlled hydraulic conditions that may not capture the full variability encountered in real rivers, such as fluctuating sediment loads, seasonal flow reversals, and biological debris. The turbine's electrical system was tested under steady-state loads, leaving dynamic or surge-related behaviours unexamined. Additionally, although modularity was proven technically effective, its long-term impact on system durability and wear—especially at interface points—requires longitudinal assessment. Local manufacturing challenges, including limited access to precision tools, may also affect reproducibility and standardisation.

To extend the impact and applicability of the system, future studies should prioritise long-term field testing across diverse hydrological zones in Nigeria and similar regions. Integrating digital control systems for load management, real-time monitoring, and predictive maintenance would significantly enhance reliability and efficiency. Hybridisation with solar photovoltaic systems and battery storage should also be explored to ensure round-the-clock energy availability during dry seasons or variable load periods. Developing partnerships with local technical colleges and community cooperatives for fabrication and maintenance training could foster local ownership and support sustainable scaling. Further, lifecycle costing and social impact assessments should be undertaken to evaluate not just the technical viability, but the economic and cultural fit of the technology in rural settings. Standardised toolkits for replication—covering design templates, assembly manuals, and maintenance protocols—should also be developed to facilitate wider adoption.

The modular crossflow mini-hydro turbine developed in this study represents a significant step forward in decentralised renewable energy innovation. It demonstrates that well-engineered, small-scale hydropower systems can be simultaneously efficient, modular, environmentally acceptable, and socially relevant. Its compatibility with the infrastructural realities of rural Nigeria makes it a strong candidate for integration into national and regional electrification strategies. With thoughtful scaling, localisation, and policy support, this system can help close the energy access gap in underserved communities, enabling improved livelihoods, economic activity, and educational outcomes. In a broader context, it contributes to climate-smart infrastructure by leveraging local water resources for sustainable energy generation without imposing ecological or social burdens. The work lays a practical and theoretical foundation for the next generation of rural energy systems—those that are modular by design, inclusive by function, and resilient by necessity.

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