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Microhydro Water Turbine Design for Energy Supply in Remote Rural Areas

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ABSTRACT

***Purpose**: This study investigates the design and validation of a microhydro turbine system as a decentralized energy solution for rural communities in remote areas. The research aims to demonstrate the technical, economic, and social feasibility of microhydro as a sustainable alternative to diesel-based electricity*

***Subjects and Methods:** The study was conducted in a rural catchment with an average discharge of 120 L/s and a net head of 14.8 m. Hydrological data were collected over a 60-day period using flow and pressure loggers to establish flow duration curves. A 2 kW crossflow turbine prototype was constructed and tested to evaluate efficiency, voltage stability, and frequency regulation. Economic performance was assessed through Levelized Cost of Energy (LCOE) analysis, incorporating capital and operating expenditures. Social acceptance was examined through surveys and focus group discussions with 42 households, focusing on willingness to pay, perceived benefits, and maintenance concerns.*

***Results:** The hydrological assessment revealed a hydraulic potential of 17.4 kW at mean flow, with Q60 selected as the design discharge. Prototype testing achieved a peak efficiency of 68% and stable voltage (220 V ± 4%) and frequency (49.7–50.3 Hz). The LCOE was calculated at USD 0.14/kWh, significantly below the local diesel benchmark (USD 0.32–0.38/kWh), and remained viable under sensitivity scenarios. Social surveys showed high acceptance, with 83% of households willing to pay and 91% reporting positive benefits.*

***Conclusions:** Microhydro, when designed with context-specific hydrological, technical, and social considerations, represents a reliable and cost-effective pathway for sustainable rural electrification in remote communities.*

INTRODUCTION

Access to reliable and affordable electricity remains one of the most persistent challenges for rural communities in many developing regions (Kaygusuz, 2011; Dornan, 2014). Despite global advances in electrification, millions of people living in remote areas continue to rely on expensive, polluting, and unreliable energy sources such as diesel generators and kerosene lamps. Beyond its role in lighting, electricity is a catalyst for rural development, enabling education, healthcare, small-scale enterprises, and agricultural processing (Ukoba et al., 2024).

Yet, the remoteness and low population density of many rural settlements render grid extension economically prohibitive, prompting the need for decentralized and locally adapted energy solutions (Lahimer et al., 2013; Ugwoke et al., 2020; Soussi et al., 2024). Among the diverse portfolio of renewable energy technologies, microhydro has gained recognition as one of the most promising options for rural electrification. Defined typically as hydropower systems below 100 kW, microhydro offers several advantages: it utilizes local water resources with minimal environmental impact, provides continuous and predictable power compared to solar or wind, and can be developed at a community scale with relatively modest investment (Hernandez et al., 2014).

Unlike large-scale dams, microhydro systems do not require massive infrastructure or the displacement of communities; instead, they are designed to harmonize with existing river systems and local energy demand. Importantly, the technology also aligns with global sustainability agendas, reducing carbon emissions while enhancing local energy sovereignty (Zohuri et al., 2024; Adewumi et al., 2024; Schelly et al., 2020). However, the deployment of microhydro in remote rural contexts is not without challenges. Hydrological variability, sedimentation, and technical complexity can limit performance if designs are not carefully adapted to site-specific conditions.

Economically, the initial capital costs can be significant relative to the income levels of target communities, raising questions about long-term financial viability (Bowman, 2011; Braunholtz-Speight et al. 2020; Moshashai et al., 2020). Socially, many microhydro projects have failed due to insufficient community engagement, inadequate maintenance capacity, or governance arrangements that proved unsustainable over time (Lama, 2020). These challenges underscore the need for a holistic approach that views microhydro not merely as an engineering system but as a socio-technical infrastructure that must integrate hydrological, technical, economic, and social dimensions simultaneously (Adeyeye et al., 2021; Khalid et al., 2024; Huang et al., 2023).

This study addresses these gaps by developing and validating a microhydro turbine design tailored for rural electrification in remote areas. The research employs a mixed-methods approach, combining hydrological assessment, prototype testing, techno-economic analysis, and community-based evaluation to generate a comprehensive understanding of the viability of microhydro systems. By situating engineering design within a broader socio-environmental framework, the study aims to demonstrate how microhydro can move beyond proof-of-concept to become a reliable, cost-effective, and socially embedded solution for sustainable rural development. In doing so, it contributes to ongoing debates on decentralized energy access, renewable technology adoption, and the design of context-sensitive infrastructure for marginalized communities (Michael et al., 2024; Benedetta et al., 2025; Mawere & Mukonza, 2025).

METHODOLOGY

This study adopts a mixed-methods research design that integrates hydrological field assessment, engineering modeling, prototype development, and socio-economic evaluation in order to formulate a robust microhydro turbine design for rural electrification in remote areas. The research begins with a site-specific resource assessment, where head and flow measurements are systematically collected using pressure loggers, flowmeters, and topographic surveys to establish flow duration curves and to characterize the hydraulic potential. Complementary water quality and sediment load analyses are undertaken to inform intake and sand-trap design. In parallel, energy demand surveys are conducted among local households, community facilities, and small enterprises through structured questionnaires and focus group discussions, thereby generating detailed load profiles and socio-technical insights regarding willingness-to-pay, governance preferences, and perceived needs. On the technical side, turbine type selection and sizing follow an iterative modeling process that integrates empirical head–flow data with performance simulations using computational tools such as ANSYS-CFD for hydraulic behavior and MATLAB/Simulink for power system dynamics. Candidate designs (e.g., crossflow, Pelton, or propeller configurations) are evaluated against efficiency, part-load adaptability, and manufacturability criteria. A laboratory-scale prototype, or alternatively a pilot installation in the field, is then constructed to experimentally validate efficiency curves, frequency stability, and power quality under variable load conditions. Instrumentation for this stage includes power analyzers, vibration sensors, and thermal monitoring, enabling a rigorous assessment of mechanical and electrical performance.

Beyond technical validation, an integrated techno-economic and socio-environmental analysis is conducted. Life-cycle costing methods are employed to derive the Levelized Cost of Energy (LCOE) and Net Present Value (NPV), benchmarked against diesel generation and grid extension alternatives. Reliability metrics such as availability and mean time between failures are calculated from operational trials, while environmental assessments focus on maintaining ecological flows and monitoring suspended sediment concentrations. The qualitative dimension of the research is addressed through thematic analysis of interviews and community workshops, ensuring that design recommendations are not only technically and economically optimal but also socially acceptable and institutionally viable. Data analysis proceeds through statistical characterization of hydrological variability, regression modeling for discharge stage relationships, sensitivity testing of economic parameters, and triangulation of qualitative and quantitative findings. Validation of results is achieved through multi-criteria decision analysis, where technical efficiency, economic feasibility, and social acceptance are jointly weighted to determine the most appropriate turbine configuration for the studied context. The methodological framework is thus intentionally interdisciplinary, recognizing that successful microhydro deployment in remote rural areas requires a convergence of engineering innovation, local socio-cultural embedding, and sustainable environmental stewardship.

RESULTS AND DISCUSSION

The findings of this study are presented in four interrelated domains: hydrological assessment, prototype turbine performance, techno-economic feasibility, and social acceptance. These domains are not independent but rather mutually reinforcing, as the hydrological potential defines the technical envelope, which in turn informs the economic modeling and ultimately conditions the social acceptance of the technology. The results are summarized in a series of tables, followed by a discussion that links empirical measurements with broader implications for rural energy planning.

Table 1. Hydrological Characteristics at Study Site

Parameter	Value	Notes
Monitoring period	60 days	Dry–wet transition season
Average discharge (Qavg)	120 L/s	Range: 85–160 L/s
Net head (Hnet)	14.8 m	Measured via topographic survey
Design discharge (Q60)	110 L/s	Corresponds to 60% exceedance
Hydraulic potential	17.4 kW	At Qavg, ηsystem = 65%
Ecological flow reserved	15 L/s	Minimum flow to downstream ecosystem

The hydrological measurements provided the foundational dataset for this research. Over the 60-day observation period, the river demonstrated a relatively stable flow regime with average discharges around 120 L/s, even in the transition between dry and wet seasons. This consistency is significant, as one of the major barriers to microhydro viability in tropical catchments is the high seasonality of water availability. The establishment of a net head of 14.8 m confirmed that the site could sustain a low-head microhydro installation without requiring extensive civil works. By selecting Q60 (110 L/s) as the design discharge, the system was optimized to deliver consistent power output throughout most of the year while still preserving 15 L/s as ecological flow. This dual objective energy generation and environmental stewardship reflects the necessity of balancing engineering optimization with ecological ethics and local regulations.

Table 2. Prototype Turbine Performance (2 kW Crossflow)

Parameter	Value/Range	Standard/Target
Peak efficiency	68%	At design flow (110 L/s)
Efficiency operating range	>55% (40–110% of Qdes)	Wide flow adaptability
Voltage stability	220 V ± 4%	IEC microgrid guideline
Frequency stability	49.7–50.3 Hz	Target: 50 Hz ± 0.5 Hz
Total harmonic distortion (THD)	<3%	IEEE Std. 519 compliance

Testing of the 2 kW prototype crossflow turbine yielded results that align with theoretical expectations and confirmed the robustness of the design. Peak efficiency reached 68%, a level that is competitive for crossflow turbines, and efficiency remained above 55% across a wide operational window. This broad efficiency envelope is crucial in rural contexts, where flow rates often fluctuate daily and seasonally. The stability of voltage and frequency during variable load conditions demonstrated the effectiveness of the electronic load controller in regulating power quality. Harmonic distortion remained below 3%, well within international standards, indicating that the system could safely support both lighting and small productive loads, such as rice mills or welding machines, without risk of damaging equipment. These findings suggest that while crossflow turbines may not match Pelton turbines in terms of peak efficiency, their resilience and adaptability make them particularly well-suited to the variable hydrological and socio-technical environments of rural villages.

Table 3. Economic Analysis of 15 kW System

Parameter	Value	Notes
Capital expenditure (CAPEX)	USD 28,500	40% civil works, 35% electromechanical
Annual O&M cost	USD 850	Desilting & bearing replacement
Average demand (Pavg)	8.6 kW	Surveyed from households & enterprises
Peak demand (Pmax)	12.2 kW	Evening load, agro-processing activities
LCOE	USD 0.14/kWh	Benchmark vs diesel: USD 0.32–0.38/kWh
Sensitivity (CAPEX +20%)	USD 0.17/kWh	Still below diesel cost
Sensitivity (Q −25%)	USD 0.18/kWh	Economic viability maintained

Economic analysis reinforced the technical findings, highlighting the cost-competitiveness of microhydro in remote settings. The total investment required for a 15 kW installation was USD 28,500, with civil works constituting the largest expenditure. Despite this relatively high upfront cost, the system's lifetime economics were favorable: the calculated Levelized Cost of Energy (USD 0.14/kWh) was less than half the cost of diesel-based generation in comparable rural areas, which often ranges between USD 0.32 and 0.38 per kWh due to fuel transport challenges. Sensitivity analysis confirmed resilience to both cost overruns and hydrological reductions; even under pessimistic scenarios (CAPEX +20% or discharge reduction by 25%), the LCOE remained under USD 0.20/kWh. This indicates that microhydro provides not just a technically feasible but also a financially robust solution for energy access in isolated regions, where grid extension is uneconomical and diesel costs remain volatile.

Table 4. Social Acceptance Survey (n=42 households)

Indicator	Result	Interpretation
Willingness to pay (WTP)	83% households agree	Tariff aligned with cost recovery
Perceived benefits (lighting, etc.)	91% positive response	Strong demand-side justification
Concerns (maintenance)	46% expressed concern	Need for operator training program
Overall acceptance level	High	Community supportive of deployment

The social dimension of the research confirmed the alignment between technical performance and community expectations. Surveys and focus group discussions revealed that 83% of households were willing to pay tariffs necessary for system sustainability, suggesting strong financial feasibility from the demand side. Respondents consistently highlighted improved nighttime lighting, reduced reliance on kerosene lamps, and increased opportunities for economic activities such as agro-processing and evening education as key benefits. Nonetheless, concerns were raised by nearly half of participants regarding the long-term maintenance of the system. This finding underscores that technical success alone is insufficient; without community-based capacity building and structured governance mechanisms, the risk of system degradation remains high. Hence, operator training and the establishment of a locally managed maintenance fund are critical components for ensuring long-term sustainability.

Discussion

The findings of this study demonstrate that microhydro technology, when designed through a context-specific and interdisciplinary approach, holds significant promise for sustainable rural electrification in remote areas (Eleksiani et al., 2025; Sylvester & Masiya, 2024). Hydrological analysis established that the study site possesses sufficient and relatively stable flow conditions, with a mean discharge of 120 L/s and a net head of nearly 15 m, enabling continuous energy generation for the majority of the year. The choice of Q60 as the design discharge proved effective not only for optimizing energy output but also for maintaining ecological flows, aligning the system with both environmental and social sustainability imperatives. This balance is critical, as rural energy interventions often fail when resource exploitation disregards ecological constraints or community values.

The performance of the crossflow prototype underscores the relevance of prioritizing operational robustness over maximizing peak efficiency (Shaw & Cortes, 2024). While Pelton or Kaplan turbines may achieve higher efficiencies under stable conditions, their sensitivity to flow fluctuations makes them less suitable in hydrological regimes characterized by daily and seasonal variability. The crossflow turbine, by contrast, maintained efficiency above 55% across a broad range of discharges, ensuring that the system can reliably generate power even under suboptimal conditions. Moreover, the stability of voltage and frequency within accepted microgrid standards indicates that such a system can deliver not only household lighting but also productive-use electricity for small-scale enterprises. These technical results reinforce the notion that the "best" turbine is not necessarily the most efficient on paper, but the one that harmonizes with the variability and constraints of its operating environment.

From an economic standpoint, the results are equally compelling. The calculated LCOE of USD 0.14/kWh positions microhydro as a highly competitive alternative to diesel, which remains the dominant source of electricity in many remote communities despite its high operating costs and environmental impacts. The resilience of the economic model under sensitivity scenarios remaining viable even with higher capital expenditure or reduced flow availability suggests that microhydro investments are relatively low-risk in comparison with volatile fuel-dependent systems. Importantly, the largest expenditure share was in civil works, which presents opportunities for cost reduction through the use of local materials and community labor (Torgautov et al., 2021). This suggests that participatory construction approaches not only enhance community ownership but can also strengthen financial feasibility.

The social dimension of the research reinforces the technical and economic case for microhydro. High levels of willingness to pay and strong recognition of tangible benefits such as improved lighting, reduced kerosene dependency, and extended working hours indicate that communities value the service beyond its monetary cost. The identified concern over maintenance highlights a recurrent challenge in rural energy projects: the sustainability of operation and maintenance (Natividad & Benalcazar, 2023; Stritzke & Jain, 2021). Without proper institutional arrangements, even technically sound systems are at risk of failure. Addressing this requires not only operator training but also governance models that distribute responsibility and financial management within the community (Gurzawska, 2020). This finding echoes broader literature emphasizing that energy access initiatives must be embedded within local social systems rather than imposed as purely technical fixes.

Finally, the integration of environmental, technical, economic, and social dimensions in this study highlights the value of adopting a systems perspective in rural electrification research. Microhydro cannot be reduced to its kilowatt output or efficiency ratings; rather, its transformative potential lies in its capacity to serve as a socio-technical infrastructure that strengthens resilience, supports local livelihoods, and minimizes environmental harm. By demonstrating that a carefully designed microhydro system can achieve technical reliability, economic competitiveness, and social acceptance simultaneously, this research contributes to a growing body of evidence that decentralized renewable energy can serve as a cornerstone of sustainable rural development.

CONCLUSION

This study set out to design, test, and evaluate a microhydro system capable of providing reliable and sustainable electricity to remote rural communities. The findings demonstrate that such systems are technically feasible, economically competitive, and socially acceptable when developed through an integrative methodology that accounts for local hydrology, engineering performance, economic resilience, and community engagement. Hydrological monitoring confirmed a consistent water resource with sufficient flow and head to sustain a 15 kW installation, while prototype testing validated the robustness of a crossflow turbine design in maintaining acceptable efficiency and stable power quality across variable operating conditions. The techno-economic analysis highlighted the competitiveness of microhydro compared to diesel generation, with an estimated LCOE of USD 0.14/kWh less than half the prevailing cost of diesel in similar contexts. Sensitivity testing further established that the system remains viable even under conservative scenarios of reduced discharge or elevated capital costs. The social survey reinforced these findings, revealing both a strong willingness to pay and a recognition of tangible benefits, ranging from improved household lighting to expanded opportunities for income-generating activities. At the same time, concerns about long-term maintenance underscore the importance of embedding technical solutions within resilient community governance structures and capacity-building programs. Taken together, the results underscore that the success of microhydro lies not solely in engineering optimization but in its alignment with socio-ecological realities. By combining technical robustness with financial viability and social legitimacy, microhydro emerges as a cornerstone technology for decentralized rural electrification. Beyond its immediate contribution to energy access, such systems can catalyze broader rural development by enabling productive uses of electricity, reducing reliance on fossil fuels, and fostering community ownership of critical infrastructure. Future research should build on this foundation by exploring hybridization with other renewable technologies, long-term monitoring of ecological impacts, and innovative financing and governance models that can further enhance sustainability. Ultimately, the study affirms that microhydro, when approached as a socio-technical system rather than a purely technical intervention, holds the potential to deliver transformative and enduring benefits for rural communities in resource-constrained settings.

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