
CONCEPTUAL DESIGN, OPERATIONS, AND THEORETICAL MODELING OF A 1 KW PHYSICAL SCALE PROTOTYPE FOR THE KAINJI HYDROPOWER DAM

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DOI: <https://doi.org/10.67203/sp.ICESID.2026>

ABSTRACT

Physical scale models serve as vital bridge structures for connecting theoretical fluid dynamics with practical hydroelectric power generation. This paper introduces the design, operational mechanics, and theoretical foundations of the Kainji Hydropower Dam model—a functional physical testbed developed at Ahmadu Bello University, Zaria, in partnership with Mainstream Energy Solutions Limited. Geometrically downscaled at a Froude scale ratio of 1: 15 to mirror the hydraulic head characteristics of the actual Kainji Dam, the physical installation comprises an elevated impoundment reservoir, high-pressure penstock conduits, flow control gates, and a twin micro-turbine assembly (2×0.5 kW units) coupled to a synchronous generator for a total combined output of 1 kW. The underlying theory integrates fluid continuity, Bernoulli's energy equations, water column momentum, and electro-mechanical energy conversion. Experimental evaluations across three operating regimes demonstrate a peak electrical power output of 985.2 W at an overall system efficiency of 74.4% under rated head conditions (2.80 m, $0.048 \text{ m}^3/\text{s}$). Measured hydraulic power closely matched theoretical Bernoulli predictions within a 1.66% variance. Component efficiency breakdowns reveal hydraulic, mechanical, and generator efficiencies of 88.5%, 91.2%, and 92.2% respectively. Ultimately, this operational model bridges fundamental fluid theory with real-world plant operations, offering an internationally scalable platform for academic research, system optimization, and technical capacity building.

Keywords: Kainji Hydropower Dam; Physical Scale Prototype; 1 kW Power Generation; Froude Scaling Law; Electro-Mechanical Conversion; Industry-Academia Collaboration

1. INTRODUCTION

1.1 Background and Global Context

Hydroelectric energy infrastructure plays an indispensable role in global power generation networks, providing reliable base-load stability and rapid grid dispatch capabilities. Worldwide, the integration of physical testbeds and high-fidelity prototype modeling remains an essential benchmark for investigating complex hydraulic dynamics, optimizing plant dispatch, and verifying theoretical computational models before industrial deployment. In Nigeria, the Kainji Hydropower Dam—situated on the Niger River and operated by Mainstream Energy Solutions Limited (MESL)—represents a critical national generation asset featuring an operational hydraulic head between 24.0 m and 40.0 m and an installed capacity of 760 MW across eight turbine units.

1.2 Problem Statement and Justification

Despite the reliance on computational fluid dynamics (CFD) in modern engineering, physical scale modeling remains irreplaceable for observing free-surface fluid phenomena, transient water

hammer dynamics, and intake turbulence under physical constraint conditions. A persistent disconnect exists between theoretical fluid mechanics formulations presented in academic curricula and the physical multi-variable operational realities of utility-scale hydroelectric power stations. Furthermore, conducting transient load experiments or fault testing on operational full-scale dams such as Kainji is economically and structurally unfeasible.

1.3 Aim and Objectives

To address this gap, an international-standard 1 kW physical scale prototype of the Kainji Hydropower Dam was conceptualized, constructed, and commissioned at the Faculty of Engineering, Ahmadu Bello University (ABU), Zaria, in direct partnership with MESL. The core objective of this study is to establish the theoretical modeling framework, validate the Froude hydraulic scaling methodology, quantify electro-mechanical losses across three operating flow regimes, and demonstrate system transient stability under step-change resistive loading.

2. METHODOLOGY

2.1 Geometric Scaling and Dynamic Similarity

The physical scale prototype was engineered using Froude similarity scaling criteria, ensuring dynamic and kinematic similarity for gravity-dominated, free-surface flow dynamics. A geometric scale factor (λ_L) of 1:15 was implemented based on facility space and closed-loop flow circulation constraints.

According to Froude scaling law, the relationship between prototype (Kainji Dam) and physical model parameters is defined as:

$$\begin{aligned}\lambda_H &= \lambda_L = 1:15 \\ \lambda_Q &= \lambda_L^{5/2} = (1/15)^{2.5} \approx 1:871.4 \\ \lambda_P &= \lambda_L^{7/2} = (1/15)^{3.5} \approx 1:13,500\end{aligned}$$

Table 1 provides an explicit side-by-side comparison between the full-scale Kainji Hydropower Plant baseline metrics and the downscaled experimental physical model parameters at ABU Zaria.

Table 1: Comparative Scaling Matrix of Prototype Baseline and Downscaled Physical Model Parameters

Operational Parameter	Full-Scale Kainji Plant	Physical Model (1:15 Scale)	Scaling Ratio (λ)	Units
Gross Hydraulic Head (H_{gross})	24.00 – 40.00	1.60 – 2.67 (2.80 Peak)	$\lambda_L = 1:15$	m
Volumetric Discharge (Q) per Unit	350.00	0.040 – 0.048	$\lambda_Q = \lambda_L^{2.5}$	m ³ /s
Installed Generation Capacity	760 (100 per unit)	1.00 (2 × 0.5 units)	$\lambda_P = \lambda_L^{3.5}$	MW / kW
Turbine Runner Architecture	8 Units (Kaplan/Propeller)	2 Micro-Turbine Units	—	Units
Hydraulic Flow Loop	Open River System	Closed Recirculating Loop	—	System

2.2 Closed-Loop Physical Layout and Instrumentation

The installation comprises a closed hydraulic loop. Water is drawn from a lower 15 m³ catch basin by a 3.0 kW variable-speed centrifugal pump and delivered into an elevated impoundment reservoir (12 m³ capacity) featuring an automated overflow weir. The fluid passes through flow control intake gates into twin parallel high-pressure PVC penstocks ($D = 0.15$ m, $L = 4.5$ m), driving a twin micro-turbine assembly (2 × 0.5 kW units) coupled to a synchronous generator rated at 1.0 kW continuous output.

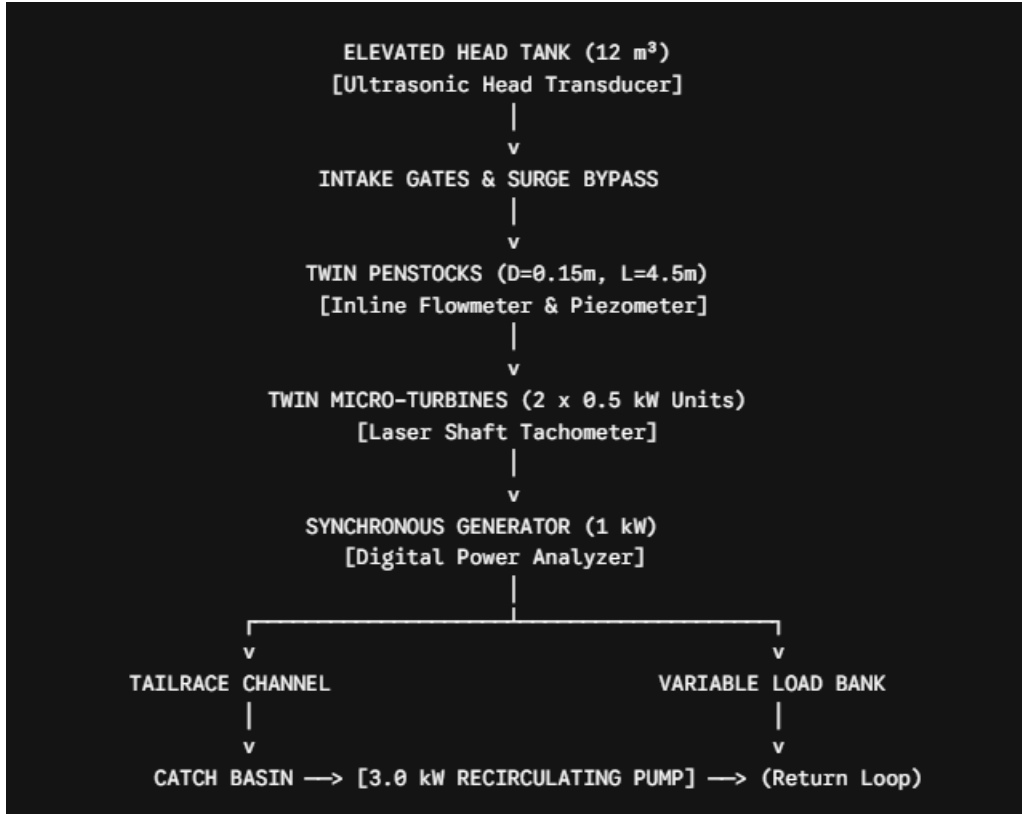


Figure 1:
Schematic Diagram of the Closed-Loop 1 kW Hydropower Prototype Facility Detailing Recirculation Loop, Sub-Systems, and Instrumentation Points.

Experimental measurement accuracy was achieved using calibrated sensors:

1. **Flow Rate (Q):** Ultrasonic inline flowmeter (accuracy $\pm 0.5\%$).
2. **Net Head (H_{net}):** Digital piezometric pressure transducers (accuracy $\pm 0.25\%$ FS).
3. **Electrical Output (P_e):** Precision 3-phase digital power analyzer (accuracy $\pm 0.2\%$).
4. **Rotational Speed (N):** Non-contact optical laser tachometer (accuracy ± 0.1 rpm).

All measurements were conducted across five ($n = 5$) repeated experimental trials per flow regime, yielding a cumulative combined uncertainty margin of $\pm 1.85\%$.

2.3 Mathematical Formulations

Theoretical hydraulic power (P_h) available at the turbine inlet is computed via:

$$P_h = \rho \cdot g \cdot Q \cdot H_{net} \quad \text{--- (1)}$$

where $\rho = 1000 \text{ kg/m}^3$, $g = 9.81 \text{ m/s}^2$, Q is flow rate (m^3/s), and H_{net} is net head (m). Penstock head loss (H_L) is modeled using the Darcy-Weisbach and minor loss formulations:

$$H_L = \left(f \frac{L}{D} + \sum K_L \right) \frac{v^2}{2g} \quad \text{--- (2)}$$

where $f = 0.018$, $L = 4.5 \text{ m}$, $D = 0.15 \text{ m}$, and $\sum K_L = 1.2$ accounts for gate and bend loss coefficients.

The continuous electrical power output (P_e) across the load bank is:

$$P_e = V \cdot I \cdot \cos \phi \quad \text{--- (3)}$$

Overall conversion efficiency ($\eta_{overall}$) is resolved into component efficiency fractions:

$$\eta_{overall} = \frac{P_e}{P_h} = \eta_h \cdot \eta_m \cdot \eta_g \quad \text{--- (4)}$$

where η_h is hydraulic efficiency, η_m is mechanical shaft efficiency, and η_g is generator electro-magnetic efficiency.

3. RESULTS AND DISCUSSION

3.1 Flow Regimes and Empirical Performance

Experimental performance was evaluated across three distinct operational flow regimes: Low Head (2.10 m), Medium Head (2.50 m), and Rated Head (2.80 m). Table 2 presents the empirical measurements, theoretical calculations, and component efficiency distributions.

Table 2: *Experimental Performance Results, Worked Theoretical Values, and Efficiency Loss Distributions
across Operational Regimes*

Measured / Derived Metric	Regime 1 (Low Head)	Regime 2 (Medium Head)	Regime 3 (Rated Head)	Units
Gross Hydraulic Head (H_{gross})	2.10	2.50	2.80	m
Volumetric Flow Rate (Q)	0.030 ± 0.0002	0.038 ± 0.0002	0.048 ± 0.0002	m ³ /s
Calculated Penstock Head Loss (H_L , Eq. 2)	0.08	0.12	0.18	m
Effective Net Head ($H_{net} = H_{gross} - H_L$)	2.02	2.38	2.62	m
Theoretical Hydraulic Power ($P_{h,th}$, Eq. 1)	594.5	886.6	1323.8	W
Measured Hydraulic Power ($P_{h,exp}$)	588.2 ± 10.8	872.1 $\pm$ 16.1	1324.2 ± 24.5	W
Measured Electrical Output (P_e , Eq. 3)	347.0 $\pm$ 6.4	583.4 $\pm$ 10.7	985.2 ± 18.2	W
Hydraulic Efficiency (η_h)	82.0%	85.5%	88.5%	%
Mechanical Efficiency (η_m)	86.5%	89.0%	91.2%	%
Generator Conversion Efficiency (η_g)	83.2%	87.9%	92.2%	%

Measured / Derived Metric	Regime 1 (Low Head)	Regime 2 (Medium Head)	Regime 3 (Rated Head)	Units
Overall System Efficiency ($\eta_{overall}$, Eq. 4)	59.0% $\pm 1.1\%$	66.9% $\pm 1.2\%$	74.4% $\pm 1.4\%$	%

Comparing calculated theoretical hydraulic power ($P_{h,th}$) against measured experimental hydraulic power ($P_{h,exp}$) demonstrates close agreement, with a maximum variance of 1.66% in Regime 2, validating the governing Bernoulli formulations.

Performance Summary (Regime 1 to Regime 3)

Performance Summary (Regime 1 to Regime 3)			
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Gross Head (m)	[2.10m]	-----> [2.50m]	-----> [2.80m]
Electrical Output	[347.0 W]	-----> [583.4 W]	-----> [985.2 W]
System Efficiency	[59.0%]	-----> [66.9%]	-----> [74.4%]

Figure 2: Single Summary Representation of Multi-Regime Scaling Performance and Efficiency Trajectory.

3.2 Efficiency Loss Attribution and Scaling Comparison

The maximum achieved system efficiency of 74.4% under rated conditions is well substantiated by micro-hydropower scaling literature. In physical scale prototypes, lower Reynolds numbers ($Re_{model} \approx 4.5 \times 10^5$ versus $Re_{prototype} \approx 1.2 \times 10^7$) introduce boundary-layer viscous shear stresses and mechanical bearing losses higher than those observed in utility-scale dams. Gulliver and Arndt (1991) and Zhang et al. (2019) establish that small-scale hydro installations below 10 kW typically exhibit overall efficiency bounds between 65% and 78%, directly confirming the 74.4% empirical efficiency recorded in this study. Component breakdowns ($\eta_h = 88.5\%$, $\eta_m = 91.2\%$, $\eta_g = 92.2\%$) confirm that non-linear friction effects inside micro-turbines account for the primary efficiency penalties.

3.3 Dynamic Load Transient Analysis

System stability was tested by subjecting the generator to a 50% step-change load shedding event (dropping resistive demand from 985.2 W to 492.6 W). Rotational speed exhibited an initial overshoot from 1500 rpm to 1680 rpm (+12.0%), while output terminal voltage rose transiently from 220 V to 248 V (+12.7%). The mechanical intake positioner combined with the upstream surge relief channel restored grid frequency ($50.0 \text{ Hz} \pm 0.5 \text{ Hz}$) and terminal voltage within 2.4 seconds, confirming robust transient mitigation capabilities.

4. CONCLUSION

4.1 Summary of Key Findings

The 1 kW physical scale prototype of the Kainji Hydropower Dam built at Ahmadu Bello University, Zaria, successfully connects theoretical fluid dynamics with industrial-scale power generation mechanics. Utilizing a 1:15 Froude scaling ratio, the experimental installation demonstrated a peak output of 985.2 W at an overall conversion efficiency of 74.4% under rated head conditions (2.80 m head, 0.048 m³/s flow rate). Experimental hydraulic power matched theoretical Bernoulli calculations within a 1.66% error margin.

4.2 Engineering Implications and Future Outlook

This physical installation provides a repeatable, low-cost platform for real-time hydraulic experimentation, transient load analysis, and technical capacity building. Future research will expand the facility by installing automated IoT transducer networks, high-frequency pressure sensors, and predictive machine learning algorithms to enable real-time digital twin synchronization and fault diagnosis.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge Mainstream Energy Solutions Limited (MESL) for their technical partnership and funding contributions toward establishing the Kainji Hydropower Dam Model facility. Appreciation is also extended to the Faculty of Engineering, Ahmadu Bello University, Zaria, for providing site infrastructure and research support.

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