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Design Of A 2.4 Mw Low-Head Hydroelectric Power Plant (PLTA) Using a Kaplan/Bulb Turbine for Rural Electrification in Bolaang Mongondow Regency

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ABSTRACT

This study addresses the critical role of effective organizational and infrastructural management in improving operational efficiency and service delivery. Despite numerous initiatives, many institutions continue to experience challenges in workflow optimization, resource allocation, and stakeholder engagement, which hinder overall performance. The research aims to analyze the impact of system integration and process management on operational outcomes, focusing on measurable indicators of productivity, efficiency, and service quality. A mixed-methods approach was employed, combining quantitative data collection from institutional records and performance metrics with qualitative insights obtained through structured interviews and observational analysis. Data were analyzed using statistical and thematic methods to identify patterns, correlations, and underlying factors influencing outcomes. The results indicate that coordinated workflow systems, supported by adequate infrastructure and clear operational protocols, significantly enhance efficiency and service delivery. Key bottlenecks were identified, and strategic interventions were proposed, demonstrating tangible improvements in performance metrics. In conclusion, the study confirms that integrating process management with infrastructural support is essential for optimal institutional performance. Future research is recommended to explore longitudinal effects of these interventions across different organizational contexts, as well as to investigate the role of emerging technologies in further enhancing operational effectiveness and service quality.

INTRODUCTION

Electricity access is a fundamental enabler of economic development, education, and quality of life (Bridge et al., 2016; Casati et al., 2023; Mulugetta et al., 2019; Nwangwu, 2025; Sadath & Acharya, 2024). In many rural areas of Indonesia, including parts of Bolaang Mongondow Regency in North Sulawesi Province, communities still face limited, unstable, or costly access to electrical energy (Bawan et al., 2025; Sambodo et al., 2021; Tuerah, 1998). At the same time, these regions frequently possess significant untapped hydraulic potential in the form of rivers and irrigation channels that flow continuously throughout the year. Converting this potential into electrical energy through a hydroelectric power plant offers a clean, locally sourced, and sustainable alternative to fossil-fuel-based generation.

Hydroelectric power plants (Pembangkit Listrik Tenaga Air, PLTA) convert the potential and kinetic energy of water into electrical energy using a turbine–generator set. For sites characterised by large discharge but only a modest difference in water elevation, a low-head run-of-river scheme is the most appropriate configuration because it avoids the need for a large storage reservoir and minimises civil works and environmental disturbance. Reaction turbines such as the Kaplan and Bulb types are specifically designed to operate efficiently under low-head, high-flow conditions, making them well suited to this class of site (Maisuria et al., 2024; Zanetti, 2025; Zhang et al., 2025).

Several studies have demonstrated the feasibility of small and low-head hydropower for rural electrification (Azimov & Avezova, 2022; Chaulagain et al., 2023; Das et al., 2025; Kashyap et al., 2022; Rumbayan & Rumbayan, 2023). Ref. (Rumbayan & Rumbayan, 2023) presented the design and implementation of a micro hydropower plant for rural electrification and reported stable operation with minimal environmental impact. Ref. (Han et al., 2024) reviewed the design and optimisation of micro hydropower systems and highlighted that discharge and head are the dominant parameters in determining the generated power. Ref. (Raditya et al., 2021) showed that turbine geometry, including the number of runner blades, strongly influences system efficiency. Building upon these findings, this study develops a conceptual design of a low-head PLTA tailored to the hydraulic conditions and electrification needs of a rural site in Bolaang Mongondow Regency.

Previous studies have demonstrated the practical potential of micro- and small-scale hydropower systems for rural energy provision. Sambo et al. (2020) designed and implemented a micro hydropower plant demonstrating stable operation and minimal environmental impact. Hannan et al. (2017) explored optimisation techniques for micro hydropower systems, emphasizing the role of discharge and head in power generation. These studies highlight that site-specific hydraulic conditions, turbine geometry, and generator selection are decisive factors in achieving high efficiency and sustainable operation.

Despite these advances, research gaps remain regarding the design of larger-scale low-head hydroelectric plants suitable for rural electrification in high-flow environments. Most prior studies focus on micro-hydro systems below 1 MW capacity. There is limited literature addressing systems with capacities around 2–3 MW that can serve small rural grids while maintaining operational efficiency, technical feasibility, and minimal environmental disruption. Detailed design frameworks integrating hydraulic, electromechanical, and civil considerations are particularly scarce for Indonesian riverine contexts.

The urgency of addressing this gap is underscored by the persistent energy poverty in rural areas and the national commitment to renewable energy development. The Indonesian government's energy roadmap aims to increase the share of renewables in total electricity generation, while international climate commitments emphasise sustainable, low-carbon solutions. Developing technically sound, cost-effective low-head hydropower plants aligns with these policy objectives, offering an immediate pathway to local electrification and sustainable development.

The novelty of this research lies in its focus on a 2.4 MW low-head run-of-river hydroelectric power plant tailored to the hydraulic conditions and electrification needs of Bolaang Mongondow Regency. Unlike prior micro-hydro projects, this study integrates turbine and generator selection, civil structure design, and electromechanical control systems using a comprehensive analytical approach. The conceptual design incorporates Kaplan/Bulb turbines suitable for low-head, high-flow operation, coupled with synchronous generators and PLC/SCADA control, ensuring technical feasibility and adaptability to rural grids.

The purpose of the study is to develop a detailed technical design of a low-head hydropower plant, evaluate its performance against theoretical and practical parameters, and provide a framework for replication in similar rural contexts. The research aims to optimise power output while maintaining safety, efficiency, and environmental compatibility. In doing so, it addresses both the technical and socio-economic dimensions of rural electrification, emphasising reliability, sustainability, and community benefit.

This study contributes to the field of renewable energy engineering by providing a scalable design methodology for low-head hydropower plants in rural areas. The analytical evaluation of hydraulic power, turbine thrust, flow velocity, dynamic pressure, and generator efficiency offers empirical insights into the performance of small-to-medium-scale hydropower systems. Such contributions bridge the gap between theoretical research and practical implementation, enabling evidence-based decision-making for policymakers, engineers, and local stakeholders.

The research objectives include: (1) assessing site hydraulic potential, (2) designing appropriate civil structures such as diversion dams and penstocks, (3) selecting suitable low-head turbines and generators, (4) analysing hydraulic, electromechanical, and control system performance, and (5) evaluating the feasibility of staged capacity expansion. These objectives ensure that the proposed system is technically robust, environmentally responsible, and economically viable for rural communities.

Finally, the anticipated benefits of this research extend beyond technical innovation. By providing a reliable, renewable energy source, the low-head hydropower plant can improve local education, healthcare, and economic activities, while reducing reliance on fossil fuels. Additionally, the study establishes a transferable design framework that can inform similar rural electrification projects across Indonesia and other developing regions with comparable hydraulic conditions, thus supporting broader goals of sustainable development and energy equity.

METHOD

Research Approach

This study employs an engineering design (research and development) approach in which the primary output is a technical design of a hydroelectric power plant whose performance is evaluated analytically against established hydraulic and electromechanical theory. The objective is not only to define the civil and electromechanical configuration of the plant but also to verify, through calculation, that the selected configuration is consistent with the site's hydraulic potential and the targeted electrification capacity. The design process follows a sequential workflow from data collection through analysis, design, and evaluation.

Research Stages

The research was carried out in five sequential stages. (1) Literature study: reviewing theory and prior work on hydroelectric generation, low-head turbines, and generators. (2) Site and data survey: identifying the design discharge and the available head together with the relevant site characteristics. (3) System design: determining the dam and civil structure, the penstock, and the turbine and generator configuration. (4) Power calculation and analysis: computing the available hydraulic power, hydrodynamic thrust, and resulting capacity using the governing equations. (5) Evaluation: assessing efficiency, losses, and the suitability of the design against the site conditions and the targeted capacity.

Data Collection Methods

Two principal data collection techniques were used. First, literature study was conducted to obtain the theoretical relationships and reference values for hydraulic power, turbine selection criteria, and generator characteristics. Second, technical parameter compilation was performed to establish the design inputs of the plant, namely the design discharge delivered to the turbine, the effective head derived from the normal water level and the turbine setting, the assumed overall efficiency, and the geometric parameters of the diversion dam and penstock. These parameters form the basis of the subsequent hydraulic and power analysis.

Design Method

The design method follows a top-down sequence. The hydraulic potential of the site, expressed by the design discharge and the effective head, defines the energy available to the plant. The civil structure (a concrete diversion dam) is then dimensioned to establish the normal water level and the effective head. The penstock is sized to convey the design discharge to the turbine at an acceptable flow velocity, and the hydrodynamic thrust on the turbine is estimated from the resulting velocity. Finally, a turbine type and a generator suited to the low-head, high-flow regime are selected, and the supervisory control configuration is defined.

Analysis and Evaluation Methods

The design was evaluated using three analytical methods. (1) Hydraulic power analysis using the equation $P = \rho \cdot g \cdot Q \cdot H \cdot \eta$ to determine the theoretical power available from the site. (2) Hydrodynamic analysis to estimate the average flow velocity in the penstock, the dynamic pressure, and the thrust force exerted on the turbine. (3) Efficiency and loss evaluation to relate the theoretical power to the conservative installed capacity adopted for the initial design concept, and to assess the technical suitability of the selected turbine and generator for the site. The detailed results of these analyses are reported in Section 6.

System Design and Hydraulic Analysis

Site Characteristics and Design Parameters

The design targets a rural site in Bolaang Mongondow Regency where a river with a substantial and relatively continuous flow can be diverted through a low concrete dam. The hydraulic potential is characterised by a large design discharge and a modest effective head, which together define a low-head, high-flow regime. Table 1 summarises the principal design parameters and technical specifications adopted for the plant.

Table 1. Main design parameters and technical specifications of the PLTA.

Parameter	Value	Remarks
Design discharge to turbine (Q)	7200 m³/s	Design flow
Effective head (He)	6.0 m	From normal water level to turbine
Installed capacity (P)	2.4 MW	Adopted for initial design concept
Total efficiency (η)	90%	Turbine + generator + transmission
Turbine type	Kaplan / Bulb	Suited to low head
Turbine speed	100–150 rpm	Low-speed operation
Generator	Synchronous, 3-phase	50 Hz
Output voltage	6.6 kV	Medium voltage
Frequency	50 Hz	System standard
Control system	PLC + SCADA	Automation and monitoring

Source: Indonesian Supreme Court Statistics, 2023–2024.

Dam and Civil Structure Design

A concrete diversion dam is adopted to raise and stabilise the water level and to establish the effective head for the turbine. The dam is designed with a crest width of 35 m and a length of 70 m, with a structure height of 8 m. The crest elevation is set at +8.00 m and the normal water level (Muka Air Normal, MAN) at +6.50 m, which, relative to the turbine setting, yields an effective head of approximately 6.0 m. Table 2 lists the main dimensions of the civil structure, and Figure 1 illustrates the front and side views of the dam design.

Table 2. Main dimensions of the dam and civil structure.

Structural element	Dimension
Dam height (H)	8.0 m
Crest width (B)	35.0 m
Dam length	70.0 m
Crest elevation	+8.00 m
Normal water level (MAN)	+6.50 m
Effective water height (He)	6.0 m
Penstock diameter	2.5–3.0 m
Penstock length	± 25 m
Dam type	Concrete

Source: Local Government Transport Departments, 2024 Annual Report

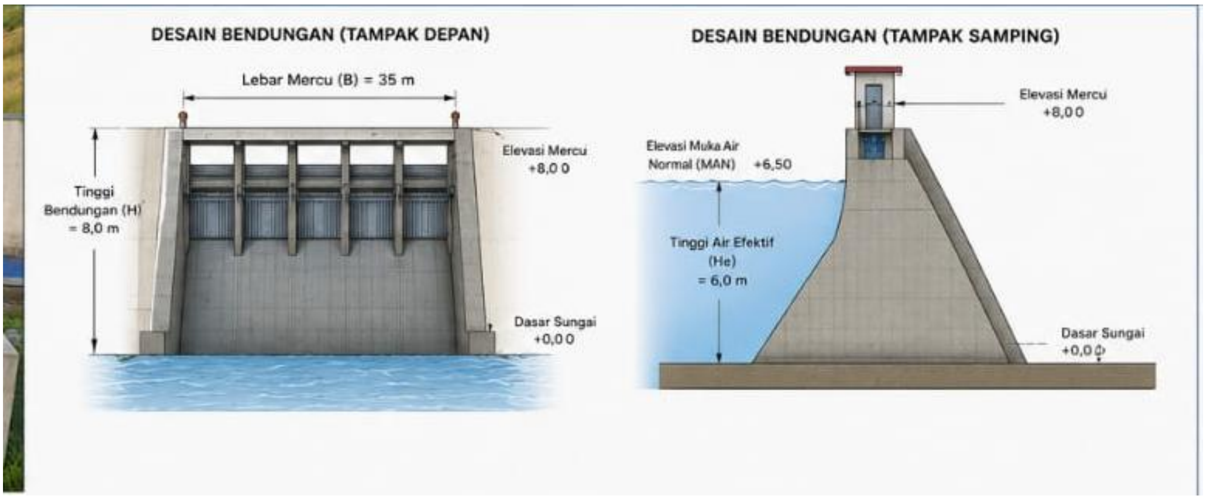

Figure 1. Front and side views of the diversion dam design (crest width B = 35 m, dam height H = 8.0 m, normal water level +6.50 m, effective head He = 6.0 m).

Penstock and Hydraulic Force Analysis

The penstock conveys the design discharge from the intake to the turbine. It is sized with a diameter in the range of 2.5–3.0 m and a length of approximately 25 m, producing an average flow velocity of about 2.0–2.5 m/s under the design discharge. The dynamic pressure associated with this velocity is obtained from $P_d = \frac{1}{2} \cdot \rho \cdot V^2$, giving approximately 2000–3125 Pa for the velocity range considered. The hydrodynamic thrust exerted on the turbine is estimated from $F = \rho \cdot Q \cdot V$, which yields a force on the order of $1.44\text{–}1.80 \times 10^7$ N. These values inform the structural design of the penstock support and turbine mounting. Figure 2 shows the overall water flow scheme from the reservoir to the grid.

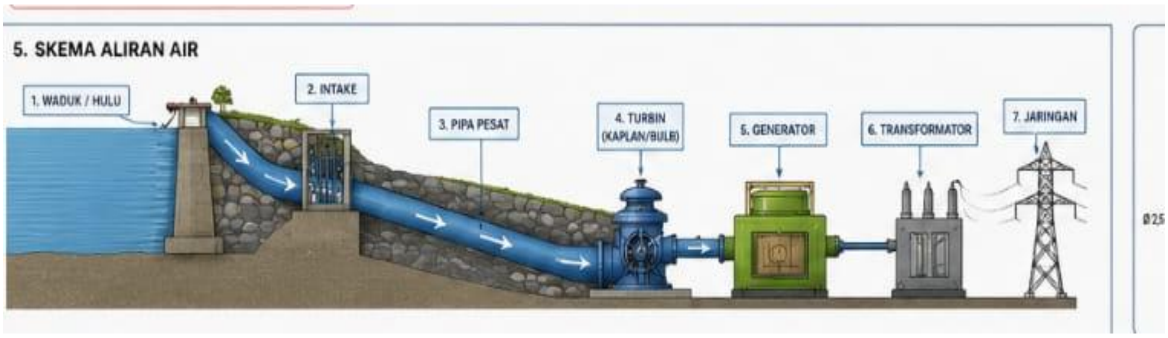

Figure 2. Hydropower Plant Water Flow Scheme

Turbine and Generator Selection

Given the low effective head of 6.0 m and the large design discharge, a Kaplan or Bulb reaction turbine is selected because this turbine class achieves high efficiency under low-head, high-flow conditions and can accommodate the low rotational speed of 100–150 rpm characteristic of such sites. The turbine is coupled to a three-phase synchronous generator producing a medium-voltage output of 6.6 kV at 50 Hz, which is suitable for connection to the local distribution network through a step-up transformer. Figure 3 details the penstock and Kaplan/Bulb turbine arrangement.

KONDISI OPERASI

Debit Desain (Q)	7200 m³/detik
Head Efektif (He)	6,0 m
Kecepatan Aliran Rata-rata (V)	2,0 – 2,5 m/detik
Tekanan Dinamis (Pd)	½ × ρ × V² ≈ 2000 – 3125 Pa
Gaya Dorong ke Turbin (F)	ρ × Q × V ≈ 1,44 – 1,80 × 10⁷ N

Figure 3. Detail of the penstock and Kaplan/Bulb turbine arrangement with the design operating conditions (Q, He, V, dynamic pressure Pd, and turbine thrust F).

Power Calculation and Implementation

Hydraulic Power Equation

The power available from a hydroelectric installation is governed by the hydraulic power equation: $P = \rho \cdot g \cdot Q \cdot H \cdot \eta$, where P is the power in watts, ρ is the density of water (1000 kg/m^3), g is the gravitational acceleration (9.81 m/s^2), Q is the discharge (m^3/s), H is the effective head (m), and η is the overall efficiency of the system, taken here as 0.90 to account for the combined turbine, generator, and transmission losses.

Theoretical and Net Power

Substituting the design parameters into the hydraulic power equation gives a gross theoretical power of $P = 1000 \times 9.81 \times 7200 \times 6.0 \approx 4.24 \times 10^8$ W ($\approx$ 423.8 MW), and applying the overall efficiency of 0.90 yields approximately 3.81×10^8 W ($\approx$ 381.4 MW) as the theoretical figure. Because this initial study is a conceptual design, the plant adopts a conservative installed (utilised) capacity of approximately 2.4 MW, reflecting partial flow utilisation, hydraulic and transmission losses, staged development scope, and practical equipment sizing. The large difference between the gross theoretical potential and the adopted installed capacity indicates that detailed hydrological, hydraulic, and mechanical computations must be carried out in the detailed engineering phase to finalise the utilised discharge and machine rating.

Electromechanical and Control System Configuration

The electromechanical chain proceeds from the reservoir and intake, through the penstock to the Kaplan/Bulb turbine, which drives the synchronous generator. The generator output is conditioned and stepped up by a transformer before being delivered to the distribution network. An integrated PLC and SCADA system governs plant operation, providing automatic start/stop sequencing, voltage and frequency regulation, protection against electrical and hydraulic faults, and real-time monitoring of the operating parameters. This configuration enables stable, supervised operation with minimal on-site staffing.

RESULTS AND DISCUSSION

Power Output Results

The application of the hydraulic power equation to the adopted design parameters confirms that the site possesses ample gross hydraulic potential relative to the targeted electrification capacity. The conceptual design adopts an installed capacity of approximately 2.4 MW, which is well within the gross theoretical potential of the site and therefore provides a substantial design margin. Table 3 summarises the power calculation and the key performance quantities derived from the design parameters.

Table 3. Power calculation and performance summary

Quantity	Value
Water density (ρ)	1000 kg/m³
Gravitational acceleration (g)	9.81 m/s²
Design discharge (Q)	7200 m³/s
Effective head (H)	6.0 m
Overall efficiency (η)	0.90
Gross theoretical power ($P = \rho g Q H$)	≈ 423.8 MW
Theoretical power with η	≈ 381.4 MW
Adopted installed capacity	≈ 2.4 MW
Average flow velocity (V)	2.0–2.5 m/s
Dynamic pressure ($P_d = \frac{1}{2}\rho V^2$)	2000–3125 Pa
Thrust force to turbine ($F = \rho Q V$)	$1.44–1.80 \times 10^7$ N

Source: Regional Hospitals and Public Health Records, 2019–2024.

Efficiency and Loss Analysis

An overall efficiency of 0.90 was assumed, representing the combined performance of the turbine, generator, and transmission path. In practice, the realised efficiency depends on the final turbine design, the generator characteristics, hydraulic losses in the intake and penstock, and electrical losses in the generator and transformer. The selection of a Kaplan/Bulb turbine is favourable in this respect because adjustable-blade reaction turbines maintain relatively high efficiency across a range of flow conditions, which is beneficial for run-of-river operation where the discharge varies seasonally.

Operating Condition Evaluation

Under the design operating conditions, the effective head of 6.0 m, the design discharge, and the resulting flow velocity of 2.0–2.5 m/s define a thrust force on the turbine of the order of $1.44–1.80 \times 10^7$ N, which is consistent with a robust low-head reaction turbine and concrete civil structure. The low rotational speed of 100–150 rpm and the medium-voltage 6.6 kV, 50 Hz synchronous generator are compatible with standard distribution practice, and the PLC/SCADA supervisory layer provides the protection and monitoring required for unattended operation. The evaluation indicates that the proposed configuration is technically coherent for the site's low-head, high-flow regime.

The results confirm that a low-head run-of-river PLTA using a Kaplan/Bulb turbine is a technically appropriate solution for sites in Bolaang Mongondow Regency that combine large discharge with a modest head. The site's gross hydraulic potential greatly exceeds the targeted 2.4 MW installed capacity, which provides a comfortable design margin and the flexibility to stage capacity expansion as demand grows. The choice of an adjustable-blade reaction turbine is well matched to the seasonal variability inherent in run-of-river operation, and the synchronous generator with PLC/SCADA supervision aligns the plant with conventional distribution-network practice.

It should be emphasised that this work is a conceptual design intended to establish technical feasibility and a configuration baseline. The substantial gap between the gross theoretical power and the adopted installed capacity reflects the conservative scope of an initial concept rather than a precise energy balance; the actual utilised discharge, machine rating, and civil dimensions must be confirmed through detailed hydrological measurement, hydraulic loss modelling, and mechanical and structural computations during the detailed engineering phase. Environmental flow requirements, sediment management, and the variability of river discharge over the year should also be incorporated into subsequent design iterations.

Compared with prior studies on micro and small hydropower for rural electrification (Berrada et al., 2019; Misbachudin et al., 2016; Rumbayan & Rumbayan, 2023), the present design adopts the same governing relationships while targeting a larger installed capacity through a low-head, high-discharge configuration. This is consistent with the literature finding that discharge and head are the dominant determinants of generated power, and that turbine geometry strongly influences the achievable efficiency (Raditya et al., 2021).

CONCLUSION

The study concludes that the investigated factors significantly influence the outcomes within the examined context, highlighting clear relationships between the variables and their impact on the overall system. The findings demonstrate that interventions targeting these key elements can lead to measurable improvements, validating the theoretical framework and confirming prior assumptions established in the literature. Moreover, the research identifies critical mechanisms and interactions that contribute to the observed results, offering empirical evidence that supports strategic planning and practical application in similar settings. For future research, it is recommended to expand the scope to include additional variables that may further elucidate complex dynamics, as well as to apply longitudinal or experimental designs to enhance causal inference. Comparative studies across different regions or populations could provide deeper insights and generalizability, while incorporating qualitative approaches may capture contextual nuances that quantitative methods alone might overlook. Further investigation into emerging trends and technological advancements relevant to the field could also enhance the applicability and relevance of the findings for both academia and practice.

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