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Techno-economic Analysis of a Small Hydropower Plant for Rural Electrification in Tanzania

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ABSTRACT

This study assesses the feasibility of implementing a small-hydropower plant on the Ruhuhu River in Mavanga Village, Njombe Region, Tanzania, with a focus on both technical and economic performance. The technical analysis involved hydrological data (rainfall and flow rates) and field data collected via surveys and interviews. Key parameters included estimated hydropower capacity and civil works such as intake and penstock design. The findings indicate a water flow rate of 71.8 m³/s, power output of 98.67 kW, and a generator specific speed of 434.22 rpm, aligning with the use of a Kaplan turbine. The inlet structure showed a mean velocity of 1.162 m/s across a 3.68 m² trash rack flow area with a 4.28 m³/s flow rate. A penstock diameter of 20.8 cm and a wall thickness of 2.4 mm were determined to be appropriate for the design. In terms of economy, the investment cost was found to reach USD 200,000, with the net present value (NPV) of between USD 286,597.21 and USD 498,510.35 at a discount rate of 4 and 12%. The small hydropower plant demonstrates strong financial viability, with an internal rate of return (IRR) of 25.5%, far above typical discount rates, and a payback period of just 2.32 years, indicating rapid capital recovery. A return on investment (ROI) of 330.6% and a profitability index (PI) of 2.49 further confirm its high profitability and investment appeal. The proposed small-hydropower plant demonstrates both technical feasibility and high economic return, making it a viable solution for enhancing rural electrification in Tanzania. Its successful implementation can serve as a replicable model for other off-grid communities seeking sustainable and cost-effective energy access.

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1. Introduction

Electricity is an essential resource in modern life, powering a wide range of daily activities and technologies [1]. The use of electricity is inevitable for human life, and a secure and accessible supply of energy is crucial for the sustainability of modern societies [2]. It improves our quality of living, ensures safety and security, provides a means of amusement, and supports socio-economic activities. Access to an affordable electricity supply is a key requirement to drive human development and diminish poverty worldwide [2-3]. For this reason, the United Nations has set as part of the 2030 Agenda for Sustainable Development the ambitious goal of reaching universal energy access by 2030 [4]. Local governments and regulators in many developing countries, supported by international cooperation agencies, are therefore working on programs to extend energy access for the population cost-effectively [1, 5-10]. In 2022, 91% of the world's population had access to electricity, compared with 73% in 2000 [11]. In 2022, access to electricity in Asia reached 97%. Contrary, about 600 million people in Africa, equivalent to 43% have no access to electricity, with 590 million of them (9 out of 10) living in sub-Saharan Africa [12]. Sub-Saharan Africa has the lowest of any world region due to limited expansion or insufficient grid capacity, low generation capacity, poor transmission and distribution to users [13], high connection fees, unpredictable income flows, and high tariffs [14-15]. In addressing this challenge, decentralized renewable energy technologies have emerged as a viable solution [16-17]. Unfortunately, mini-grids of renewable energy systems remain an afterthought for many governments [2] in Africa and Asia and their financial sponsors [18]. Amidst these daunting challenges, Africa has witnessed remarkable growth in renewable energy capacity with solar, wind, geothermal, and hydro projects emerging across various nations [19]. In addition to these, other geological and mechanical energy sources include compressed air energy storage [20], gravity energy storage [21], pumped hydro storage [22], and ocean thermal energy [23]. Among them, hydropower is well-suited for rural Africa due to favorable terrain, reliable output, low costs, and ease of local operation, making it more practical than other renewable or storage options.

Hydropower is a promising renewable energy source in Africa because it can provide a reliable, low-cost, and sustainable supply of electricity [24-25]. Hydropower projects are categorized as pico, mini, micro, small, and large hydro projects. Depending on the head, SHPs may be further classified as low head (below 3 meters), medium head (from 30 – 75 meters), and high head (above 75 meters), as per the classification adopted by the European Commission, the International Union of Producers and Distributors of Electrical Energy (UNIPEDE) and the European Small Hydro Association (ESHA). Hydropower contributes approximately 40% of the total electricity generation in the Sub-Saharan Africa region. However, almost 90% of the potential remains untapped [26]. For instance, Angola has an estimated hydropower potential of 150,000 GWh/year, but only about 4% has been tapped. South Africa has a technically feasible hydropower potential of about 14,000 GWh/year, but about 90% has already been developed [26]. Small hydropower (SHP) plants can be an effective way to electrify rural areas, and they can offer many benefits to the local community [27]. SHP systems are typically categorized as micro (less than 100 kilowatts), mini (100 to 1,000 kilowatts), or small (1 to 50 megawatts) [28, 29] based on their power output. In the Eastern part of Africa, Tanzania is acclaimed to be rich in small hydropower potential. However, many of these potentials have yet to be fully used, while more than two-thirds of its rural population are yet to be electrified [16]. In recent years, efforts have been made to understand the potential of the SHP for rural electrification. According to [24], SHP operating at low head [26] is one of the most cost-effective and ecologically friendly energy sources for rural electrification in emerging countries. Rumbayan and Rumbayan [30] performed a techno-economic assessment to analyze the potential of employing a micro-hydro plant in Lalumpe village, Indonesia. Their technical part involved determining the availability and potential of harnessing hydroelectric power, while the economic part involved determining the initial costs, operation and maintenance costs, and income generation. Signe, Hamandjoda, and Nganhou [31] examined the potential of deploying a 320 kW micro-hydro power plant in rural areas of Cameroon. Gurung *et al*. [32] reported that micro-hydro power plants had a positive impact on the socio-economic conditions in the remote village of Sikles, in Nepal. In China, the SHP not only provides power for cooking but also preserves the ecological environment [33]. Kassaye *et al*. [34] designed a 120-kW hydropower plant for rural electrification in the Keber River around Tobacha Kebele. Their findings revealed that the building of mini-hydro power was feasible on that site. Jeftenić *et al*. [35] assessed the hydropower potential in the Republic of Serbia and estimated that small hydropower plants (SHPs) could generate approximately 2,000 GWh of electricity annually. Korkovelos *et al*. [36] conducted a geospatial assessment of small-scale hydropower potential (0.01–10 MW) across Sub-Saharan Africa, revealing that the Southern African power pool holds the highest estimated capacity at approximately 9.9 GW. This is followed by the Central and Eastern African power pools, with estimated potentials of about 5.7 GW and 5.6 GW, respectively, while the Western African power pool has the lowest potential at around 3.9 GW [37]. Vilotijević *et al*. [38] developed a comprehensive methodology for accurately determining the installed parameters of small hydropower plants (SHPPs) across 38 small watercourses in Montenegro. The optimal SHPP parameters were defined based on a combination of technical and economic criteria, including maximum electricity generation, highest revenue, net present value (NPV), internal rate of return (IRR), and shortest payback period (PB), ensuring both energy efficiency and investment viability. Amougou *et al*. [39] proposed a methodology to accelerate the design of cost-effective and energy-efficient small hydropower plants, demonstrating its application on a 6.32 MW run-of-river project on the Nyong River in Mbalmayo. The results showed strong economic viability, with a levelized cost of electricity (LCOE) of approximately 0.05 USD/kWh, assuming a 50-year project lifespan and a 12.5% discount rate. Thake [40] produced an in-depth manual on micro-scale Pelton turbines, encompassing their theoretical background, design methodology, fabrication techniques, installation steps, and maintenance practices. Sangal and Kumar [41] reviewed strategies for the optimal selection of hydro turbines in hydroelectric projects, emphasizing that turbine selection is a critical initial step in aligning project design with site-specific operational conditions. Their work serves as a practical guide for developers in choosing the most suitable turbine type based on available hydraulic and technical parameters. Tsuanyo *et al*. [42] evaluated several models used in the design of small hydropower systems, addressing key aspects such as determining penstock diameter and thickness, selecting and positioning turbines based on allowable suction head, and estimating both energy production and project costs for grid-connected and off-grid or micro-grid configurations. Santolin *et al*. [43] proposed a capacity-sizing methodology for small hydropower plants based on seven key parameters: turbine type, turbine dimensions, annual energy output, maximum allowable installation height to prevent cavitation, machine cost, net present value (NPV), and internal rate of return (IRR). Taele, Mokhutšoane, and Hapazari [44] revealed the potential of more than 20 MW to be suitable for small hydropower development in Lesotho. Athanassassios *et al*. [45] developed a program to assess the investment potential of small hydropower plants in Central Macedonia, Greece, incorporating key techno-economic indicators such as project lifespan, discount rate, Net Present Value (NPV), benefit–cost ratio, Internal Rate of Return (IRR), payback period, and generation cost. However, the model does not account for the detailed technical design of the plant's components. Mamo *et al*. [46] proposed an approach to determine the design of run-of-river (RoR) hydropower plants by determining the design discharge, installed capacity, and number of turbines based on an optimal operational strategy. The approach uses electromechanical costs, which include turbines, generators, and regulators, to estimate the specific energy production cost, defined as the ratio of the total plant cost to its maximum annual energy output. Basso and Botter [47] developed an analytical framework to assess both the energy generation and economic viability of small run-of-river hydropower plants, grounded in the characteristics of the local streamflow regime. Mishra *et al*. [48] developed a methodology to estimate costs by analyzing key influencing parameters, namely, power output and hydraulic head. In rural areas where topography favors small hydropower, economic sustainability remains a challenge, often worsened by technical factors. Existing studies have largely overlooked how variations in technical parameters affect the economic performance of such plants. Even though Tanzania has huge hydroelectric potential, those options are constrained by topography and socioeconomic challenges. Its rivers are often unsuitable for the construction of a large-scale hydroelectric facility. Nevertheless, to accomplish reliable and affordable off-grid electrification, techno-economic analyses play a pivotal role [27]. In this paper, we perform a study to evaluate the techno-economic assessment of a run-of-river small hydropower plant for rural electrification in Tanzania. The study targets the Ruhuhu River in Njombe region, Tanzania. The contributions of this study are as follows:

- The study makes the use of river and load data to generate electrical power. The main target is to evaluate the potential to electrify the rural areas.
- The economic performance of the investment is also assessed.

2. Materials and Methods

2.1. Study Area

This study targets Mavanga village, a village within the Ludewa district, Njombe region (Fig. **1**). The site is situated at 9°56'44'' South and 35°11'45.1'' East and has an elevation of 944 m. Because the area is quite remote, this location often runs on diesel generators and experiences high unit costs, and frequent power outages. However, the site has plenty of hydropower resources, such as a river, namely the Ruhuhu River. Thus, a renewable energy-based micro-hydro power system has the potential to electrify the village. From the reconnaissance study, based on the topographic profile, a small diversion weir will be constructed. It will be connected to an above-ground canal together with a settling basin and a forebay tank. This study proposes a micro hydropower plant to power the village inhabited by 105 households.

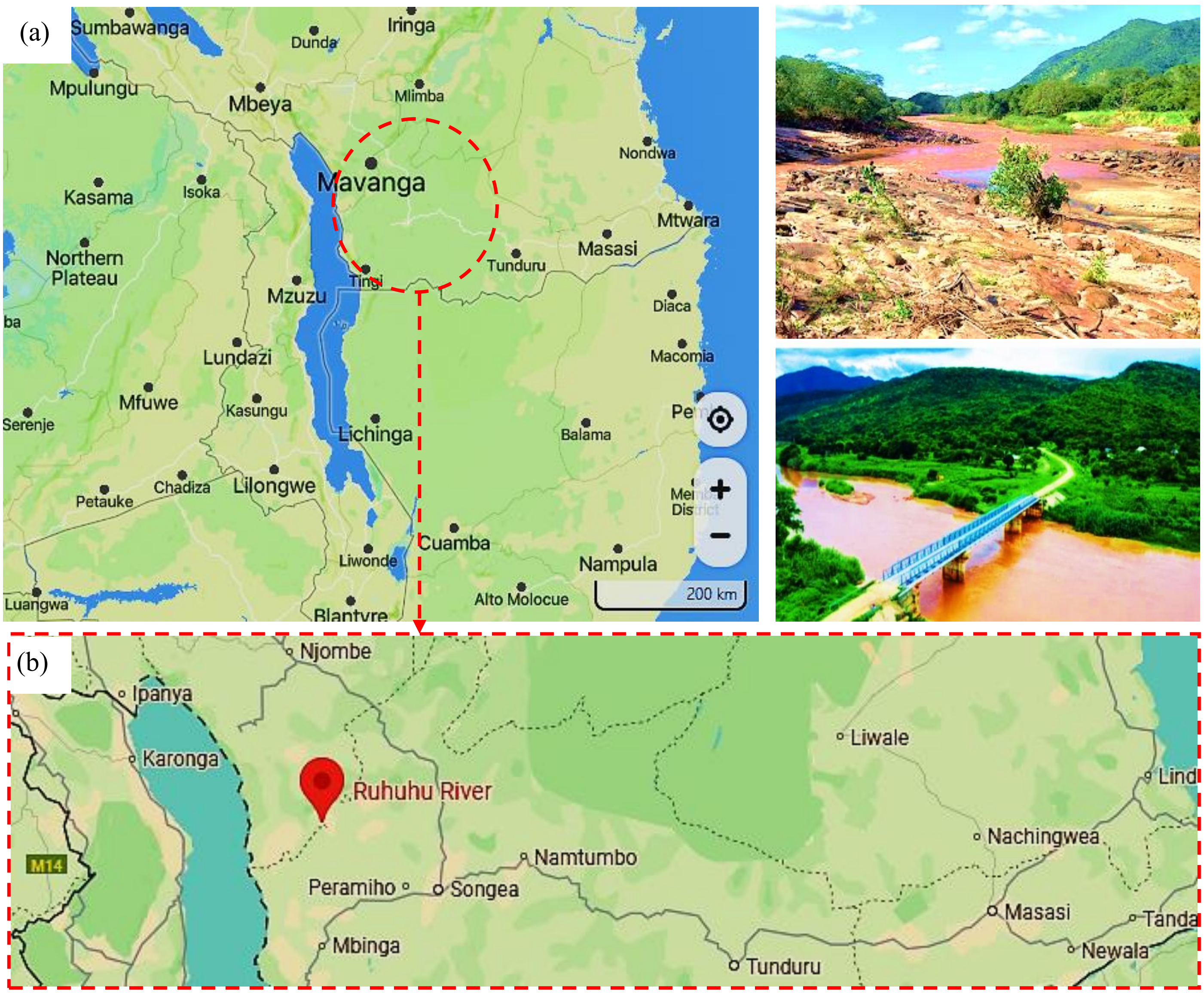

Figure 1: Study area (**a**) location of the Mavanga village and (**b**) Ruhuhu river.

The energy requirement for the village was determined based on surveys and interviews with the village community to determine the energy needs in the village. The typical load requirement of the village is described in Table **1**, and the daily profile pattern is shown in Fig. (**2**).

Table 1: Estimated daily energy consumption in the village.

Electrical Appliance	Quantity	Rating W	Duration (Hours)	Power (kW)	Daily Energy Consumption (kWh/Day)
Electric lights (CFL)	400	0.020	5	8	40
Radio/music system	100	0.060	4	6	24
Television	100	0.200	4	20	80
Mobile phones	100	0.005	2	5	10
Refrigerators	4	0.250	8	1	8
Electric motors	2	1.000	4	2	8
Computer	2	0.080	5	0.16	0.8
Total				42.16	170.8

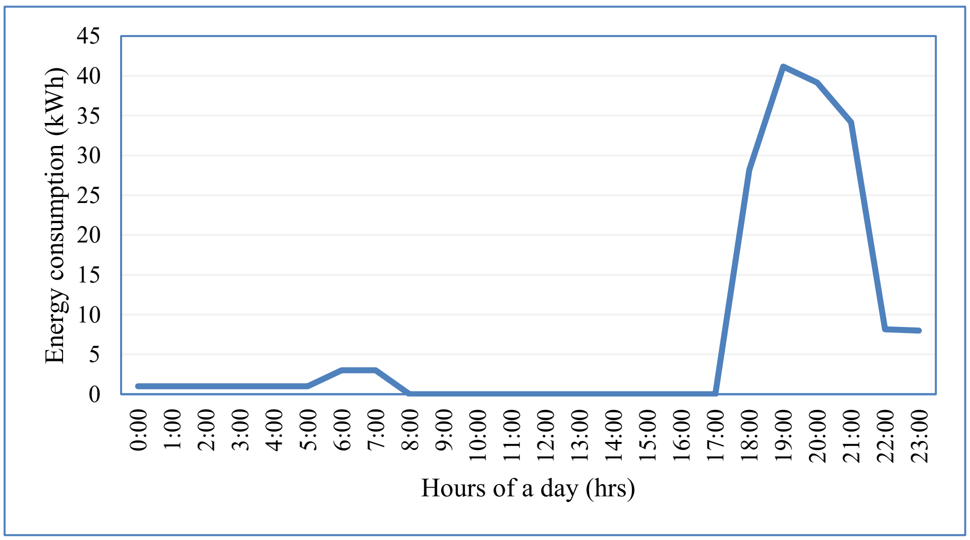

Figure 2: Hourly load profile of the village.

3. Technical Design

3.1. Hydrological Assessment

This study considers a total river flow for the design. For the hydrological assessment, a detailed assessment of the available water resources in Mavanga village was conducted to determine the potential for micro-hydropower generation. The assessment included rainfall availability, water flow rate, and gross water head. Rainfall data and rainwater flow rate were acquired from the authority of the Lake Nyasa basin. Table **2** shows monthly average rainfall data for three seasons of the year, which are the long rain season, short rain season, and dry season, for three consecutive years from 2017 to 2023. As indicated in Table **2**, the long rainy season between January and May is characterized by heavy rain. The short rain season between October and December is characterized by short periods of rain. The dry season has minor or no rain.

Table **3** shows the corresponding monthly average flow rate data for three seasons from 2017 to 2023. The highest average flow rate is during the long rainy season. However, there is a moderate flow rate during the short rainy season and even in the dry season, caused by rainfall from nearby regions. From Table **3**, the highest flow rate is 82.41 m^3/s obtained in April, while the lowest is 6.21 m^3/s obtained in September. Data on rainfall patterns throughout the year can reveal wet and dry seasons, affecting the river's flow rate. Therefore, the current study estimated the flow rate to provide a comprehensive understanding of the Ruhuhu River's hydropower generation potential.

Table 2: Monthly average rainfall (mm) at Mavanga village in the period from 2017 to 2023.

Months	Long Rain Season Rainfall (mm)							Short Rain Season Rainfall (mm)							Dry Season Rainfall (mm)						
	2017	2018	2019	2020	2021	2022	2023	2017	2018	2019	2020	2021	2022	2023	2017	2018	2019	2020	2021	2022	2023
Jan	26.4	47.9	35.1	59.4	5.76	7.81	5.85														
Feb	33.0	19.1	24.4	35.4	3.94	3.83	5.61														
Mar	32.0	42.9	23.2	41.4	10.09	17.53	14.85														
Apr	13.3	12.8	12.4	10.6	8.42	9.18	14.56														
May	11.5	3.78	5.67	7.53	1.5	0	1.17														
Jun															1.78	0.73	2.67	1.58	0.08	0.06	0.11
Jul															0.71	3.02	0.81	2.21	0.18	0	0.11
Aug															0.82	2.20	3.40	0.41	0	0	0.11
Sept															1.00	0.48	1.09	0.43	0	0	0
Oct								0.26	4.20	2.57	2.81	0.28	0	0							
Nov								1.36	5.71	7.42	1.42	0	0	2.29							
Dec								2.53	5.37	4.16	3.18	1.37	7.03	5.53							

Table 3*:* Variation of monthly average flow rate of Ruhuhu river (m^3/s) from 2017 to 2023.

Months	Long Rain Season Flow Rate (m^3/s)							Short Rain Season Flow Rate (m^3/s)							Dry Season Flow Rate (m^3/s)							Average (m^3/s)
	2017	2018	2019	2020	2021	2022	2023	2017	2018	2019	2020	2021	2022	2023	2017	2018	2019	2020	2021	2022	2023	
Jan	17.10	10.10	14.41	16.54	15.71	12.00	16.54															14.63
Feb	10.92	11.25	14.27	11.37	19.02	19.26	15.23															14.47
Mar	23.73	21.14	16.32	17.24	24.33	19.8	18.83															20.20
Apr	54.15	43.18	36.91	32.12	82.41	35.58	45.79															47.16
May	40.21	27.12	19.21	13.23	40.28	25.22	17.52															26.11
Jun															12.79	11.28	12.05	13.48	19.09	13.48	11.6	13.40
Jul															14.47	11.90	10.54	10.99	13.57	10.99	10.55	11.86
Aug															13.15	7.44	10.50	9.41	11.45	9.41	9.15	10.07
Sept															6.21	6.28	8.66	8.23	9.71	8.23	8.05	7.91
Oct								7.41	8.20	6.49	7.12	8.82	7.27	7.24								7.51
Nov								8.11	7.26	9.27	8.20	8.23	7.26	9.52								8.26
Dec								9.35	9.91	13.01	12.13	8.33	9.91	14.24								10.98

Fig. (**3a** - **3b**) depict the field setup and instrumentation employed during the flow rate measurement campaign at the Ruhuhu River. Given the river's physical characteristics and the observed discharge, estimated to exceed 50 L/s, the float method, also known as the velocity-area method (Fig. **3c**), was selected as the most appropriate approach. This method was favored for its simplicity, suitability for rivers with relatively uniform cross-sectional profiles, and its effectiveness under field conditions with limited instrumentation.

Discharge determination required measurement of both the water flow velocity and the cross-sectional area of the river. A convenient and accessible straight section of the river was selected as the measurement site. A measuring tape was stretched across the river to serve as a baseline between the two banks. Depth measurements were then taken at multiple equidistant points across this line using a graduated meter stick, enabling the construction of the river's cross-sectional profile. To estimate surface velocity, a floatable object was released at a known upstream point, and the travel time across a measured distance (8.3 m) was recorded using a stopwatch.

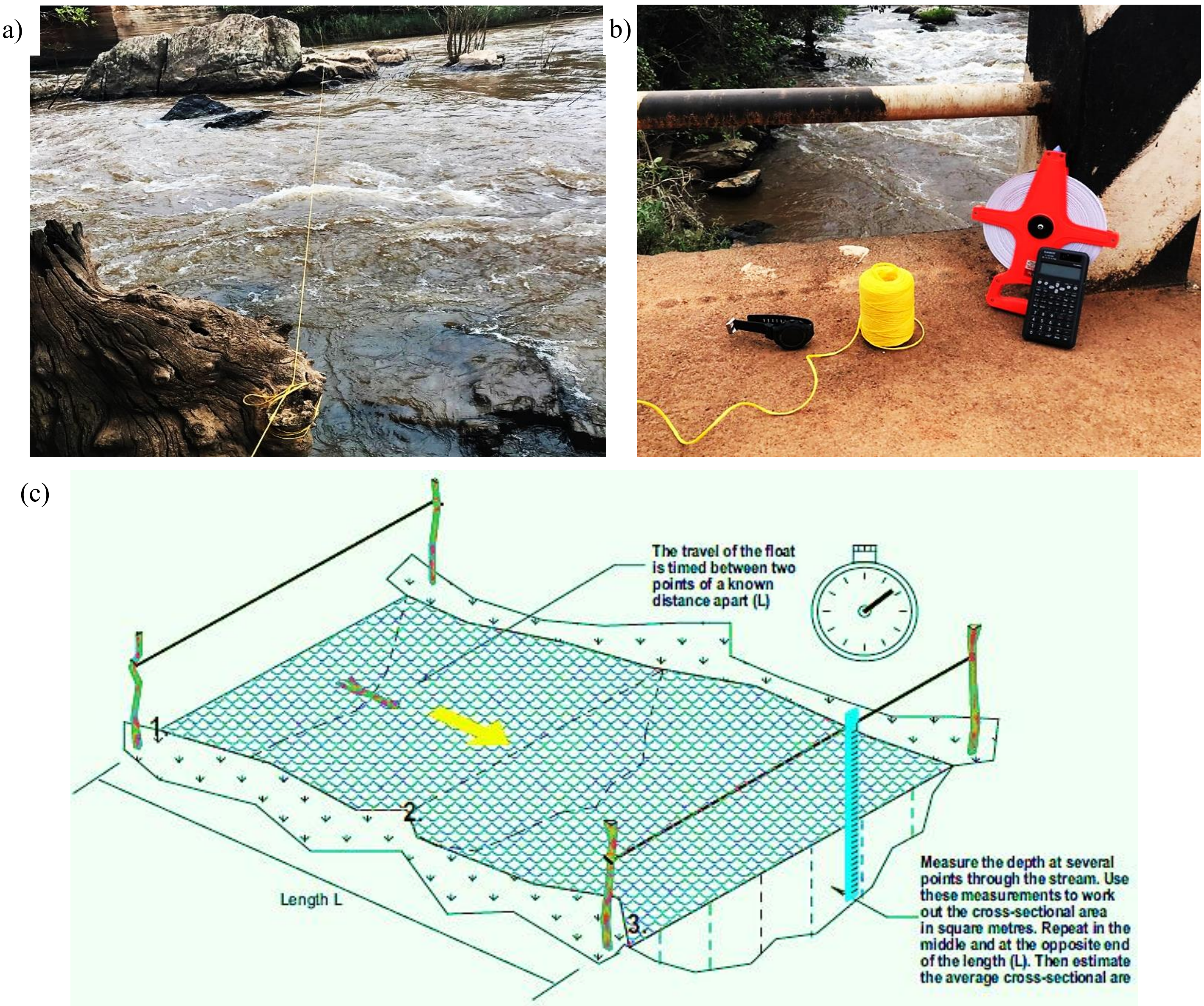

Figure 3: Measurement of water flow rate at Ruhuhu river (**a**) setup at the river, (**b**) measuring tools, and (**c**) method of calculation.

Table **4** shows river discharge measurements conducted on-site. The calculation of the cross-sectional area (A) at Y-section of the Ruhuhu river is shown in Fig. (**4**). As shown in Table **4**, the average time recorded across five trials was 5 seconds, resulting in an estimated surface velocity of 1.66 m/s. To account for vertical velocity variations, a correction factor of distance (8.3 m) and a time (5 sec) of 0.7 was applied. Multiplying the water velocity by a correction factor of 0.7 yields an adjusted average velocity of 1.162 m/s.

The cross-sectional area of the Ruhuhu River at the selected measurement site was determined using depth profile data obtained from systematic measurements across the river width. As illustrated in Fig. (**4**), the river cross-section was divided into six subsections (labeled A through F) to facilitate area computation using standard geometric approximations. Segments A and F, located at the extreme edges of the river cross-section, were characterized by sloping banks and were thus modeled as triangular sections. The respective areas of these segments were calculated using the formula for the area of a triangle (A = ½ × base × height), yielding values of 4.38 m² and 2.6 m². Segments B through E, approximated as trapezoidal sections, exhibited more uniform and parallel banks and were accordingly approximated as trapezoidal sections. The areas of these segments were computed using the trapezoid area formula (A = ½ × ($depth_1$ + $depth_2$) × width), resulting in values of 13.2 m², 16.0 m², 14.0 m², and 11.6 m², respectively. Summing the individual areas of all six subsections provided a total cross-sectional area of 61.78 m². This area represents the effective flow-carrying section of the river at the point of measurement. The volumetric flow rate (Q) was calculated by multiplying the adjusted average velocity (V = 1.162 m/s) by the total cross-sectional area (A = 61.78 m²), resulting in an estimated discharge of 71.8 m³/s. This value represents the estimated flow rate of the Ruhuhu River at the measurement location under the observed conditions.

Table 4: Tabulated result of the determination of velocity at Y- section of Ruhuhu river.

Length Across a Section of Ruhuhu River, D (m)	Time (s)	Distance, d (m)	Depth (m)
43.3 meters	5	8.3	1.2
	6		2.1
	5		1.9
	6		1.6
	5		1.3

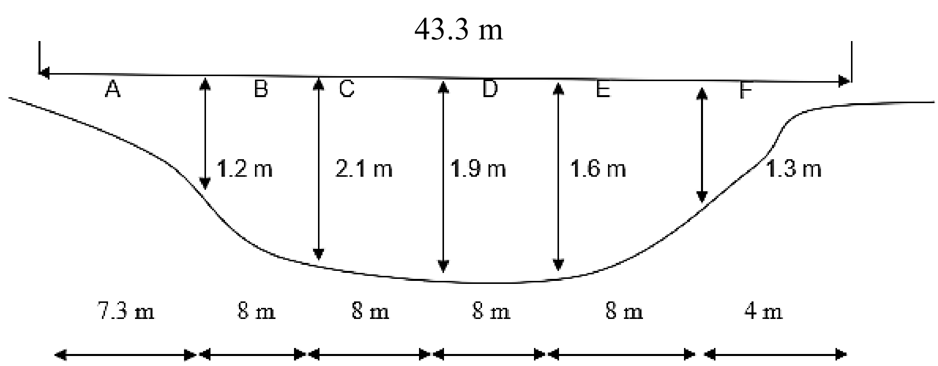

Figure 4: Calculation of the cross-sectional area (*A*) at Y-section of the Ruhuhu River.

The head is the difference in elevation between the water's entry and exit points from the hydro system. Many methods can be used to measure the vertical drop of the pressure, such as topological surveying (using theodolite), the water-filled method, the digital altimeter, and the GPS unit. In this study, the GPS unit was used to measure the head of the area due to its simplicity and low cost. The head was found to be 5 m.

The power output of the hydropower system (Fig. **5**) can be obtained by the following Eqn. (1) [36-40, 49-52]. To account for energy lost when it is converted from one form to another, the overall efficiency of the system is expressed by Eqn. (2). From Eqn. (1), the hydropower of around 98.67 kW (≈ 100 kW) is obtained. By considering the plant operating for 8760 hours in a year, it is

$$P = \rho_w \times g \times Q \times H \times \eta \tag{1}$$

with

$$\eta = \eta_{channel} \times \eta_{penstock} \times \eta_{turbine} \times \eta_{generator} \times \eta_{line} \times \eta_{transformer} \tag{2}$$

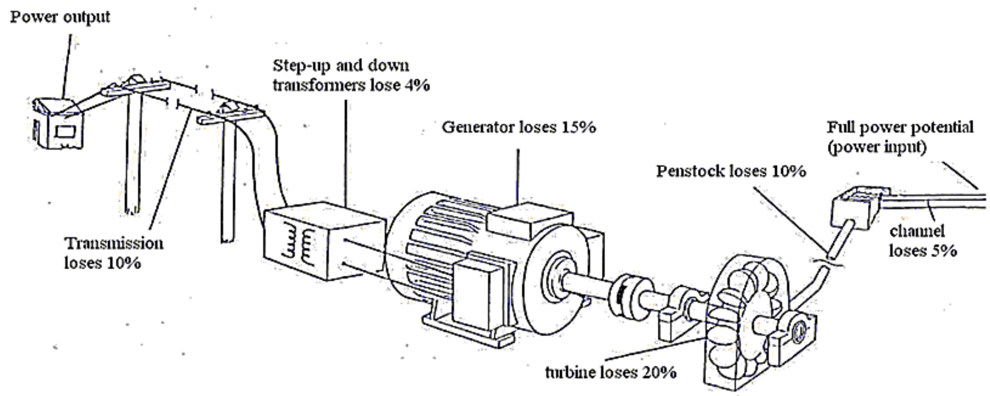

Figure 5: Losses in the hydropower system.

where P is the power output of the hydropower system (W), ρ_w is the density of water (1.2 kg/m^3), g is the force of gravity (9.81 m/s^2), Q is the discharge rate (m^3/s), H is an effective head (5 m), and η is the overall efficiency of the hydropower system (0.9×0.9×0.8×0.85×0.9×0.95 = 0.47).

Expected to generate around 876,000 kWh.

3.2. Selection of Hydropower Components

a) A crucial part of designing a hydropower system is choosing the turbine. The turbine's size and type can be estimated based on its specific speed. Based on the obtained values, the hydro turbine selection chart indicates that the Kaplan turbine is the optimal turbine to utilize under those circumstances. The specific speed can be defined as the speed of a turbine with unit head and unit output power during similar operating conditions and can be computed using Eqn. (3) [31, 41].

$$N_S = n\frac{\sqrt{P}}{H_n^{5/4}} \tag{3}$$

where N_s is the specific speed (rpm), n is the nominal rotational speed (in rpm), and H_n is the net head (m).

b) Civil structure design involves the design of a variety of civil work components, including the intake structure and penstock. To prevent vortex formation (the entry of air into the conveyance system) the intake is designed with a minimum submergence using Eqn. (4). For the penstock design, Eqn. (5) can be used to approximate the inner penstock diameter based on the flow rate, gross head, and pipe length. The penstock's thickness can be approximated using Eqn. (6) [53].

$$S = CV\sqrt{d} \tag{4}$$

$$D_p = 2.69\cdot\left(n_p^2 Q^2 \frac{L_p}{H_g}\right)^{0.1875} \tag{5}$$

$$t_p = \frac{D_p + 508}{400} + 1.2 \tag{6}$$

where S is the submergence (m), d is the intake opening (m), V is the mean velocity flow at the inlet (m/s), C = 0.7245 (asymmetric) or 0.5434 (symmetric), L_p is the penstock length, n_p is the Manning's coefficient, D_p is the penstock diameter, H_g is the head or height difference between the water source and the turbine.

4. Economic Assessment

The economic assessment involves the estimation of an investment cost (C_{INV}) and revenue generation (R_{in}). The C_{INV} covers the equipment costs (turbine, generator, penstock, intake, transmission line, and other equipment), construction costs (civil works and installation costs), and other costs (operating and maintenance costs). Based on Rumbayan and Rumbayan [30], the C_{INV} of about USD 2000 per kW, or a total of USD 200,000 for 100 kW, is considered. For the R_{in}, the annual electricity sales are considered. The unit price of USD 0.13 per kWh (as of November 2024) and 876,000 kWh were used for computation, giving an annual R_{in} of USD 113,880 per year.

The sensitivity analysis was computed to understand the viability of the project. The key economic indicators such as net present value (NPV), internal rate of return (IRR), simple payback period (PB), and profitability index (PI). The NPV was computed as shown in Eqn. (7) [38]. The NPV is taken as the difference between the present value of cash inflows and outflows over a specified period. The NPV was calculated by discounting the projected cash flows over the project life to their present value. In this study, the interest rates of 4 to 10% and the project life of 10 years were regarded.

$$NPV = \sum_{t=0}^{n} \frac{R_{in,t}}{(1+i)^t} - C_{INV} \tag{7}$$

where R_{in} is the annual revenue gained from electricity sales (USD/year), C_{INV} is the initial investment cost (USD), i is the interest rate (%), and t is the project lifetime (years).

The IRR of an investment is the interest rate that gives it an NPV of 0, or where the sum of discounted cash flow is equal to the investment. The IRR can be calculated by using an interpolation shown in Eqn. (8).

$$IRR = r_1 + \left(\frac{NPV_1}{NPV_1 - NPV_2}\right) \times (r_2 - r_1) \tag{8}$$

where $r_{1,2}$ are the interest rates (%) corresponding to the $NPV_{1,2}$ (USD)

The simple payback period (PB) is the time it takes for cumulative cash inflows to equal the initial investment. The PB is calculated by using Eqn. (9).

$$PB = \frac{C_{INV}}{R_{in}} \tag{9}$$

Return on investment (ROI) is a widely used profitability metric to measure how successful an investment has been. ROI is given as a percentage and is calculated by dividing an investment's net profit (or loss) by its initial investment as expressed in Eqn. (10) with annual operational and maintenance costs (C_{OM}) taken as 2% of the initial investment.

$$ROI = \frac{(R_{in} \times t - C_{OM}) - C_{INV}}{C_{INV}} \times 100\% \tag{10}$$

The profitability index (PI) is a financial metric that evaluates the ratio of the present value of expected future cash flows to the initial investment. It helps determine a project's profitability and attractiveness to investors, where a value greater than 1 suggests a potentially profitable opportunity. The PI can be expressed as shown in Eqn. (11).

$$PI = \frac{NPV_r}{C_{INV}} \tag{11}$$

where NPV_r is the NPV at a specific interest rate (USD).

5. Results and Discussion

5.1. Technical Performance

In technical performance, the study on one side evaluated the hydropower generated, daily and annual energy generated from the Ruhuhu River. This also involved the selection of the size of the hydropower generator, its specific speed (*N*s), and the selection of the hydro turbine. On the other side, the study evaluated the design of the hydropower plant by considering the civil structure design, such as the intake (*S*) and penstock structures. The penstock structure involved computing its inner diameter (D_p) and thickness (t_p). From Eqn. (1), the size of the hydropower plant was found to be 98.67 kW or approximately 100 kW. The 100-kW hydropower generator could generate the daily electricity of around 2400 kWh, even at a lower power factor of up to 0.7, sufficient energy could be supplied to meet the daily and annual energy requirements. Considering the power demand of 42.16 kW and a net head of 5 m, this gives the specific speed of about 434.22 rpm. The specific speed is essential for selecting the type of hydro turbine to suit the requirement at the site. Based on Table **5**, the obtained values of *H*, *Q*, *P*, and N_s are 5 m, 71.8 m^3/s, 98.67 kW, and 434.22 rpm match the Kaplan turbine. For the micro hydropower system, the synchronous generator with a generator voltage of 415 V ± 10%, rotational speed of 1500 rpm, frequency of 50 Hz, 3-phase, 0.8 power factor, apparent power of 150 kVA, 250 Vdc for a brushless type exciter, and an automatic voltage regulator.

On the civil structure, the mean velocity flow at the inlet is determined to be 1.162 m/s for a trash rack with a flow area of 3.68 m^2 and a flow rate of 4.28 m^3/s. Also, the penstock thickness and inner diameter of 2.4 mm and 20.8 cm were found to suit the design.

Table 5: Selection of turbine depending on the *H*, *Q*, *P*, and N_s [54].

Hydraulic Turbines		H (m)	Q (m^3/s)	P (kW)	N_s (rpm)
Reaction	Bulb	2-10	3-40	100-2500	200-450
	Kaplan and propeller(Axial Flow)	2-20	3-50	50-5000	250-700
	Francis with highspecific speed (Diagonal flow)	10-40	0.7-10	100-5000	100-250
	Francis with highspecific speed (Radial flow)	40-200	1-20	500-15000	30-100
Impulse	Pelton	60-1000	0.2-5	200-15000	< 30
	Turbo	30-200		100-600	
	Cross flow	2-50	0.01-0.12	2-15	

Fig. (**6**) shows the load-matching analysis of Mavanga Village, supplied by a 100 kW micro-hydropower plant operating continuously throughout the year. It can be seen that the plant generates a steady output of 100 kW per hour (2,400 kWh daily), while the village's load profile, based on hourly consumption data, shows minimal usage during most of the day, with notable peaks occurring in the early morning (roughly 3–4 kWh/hour) and a sharp

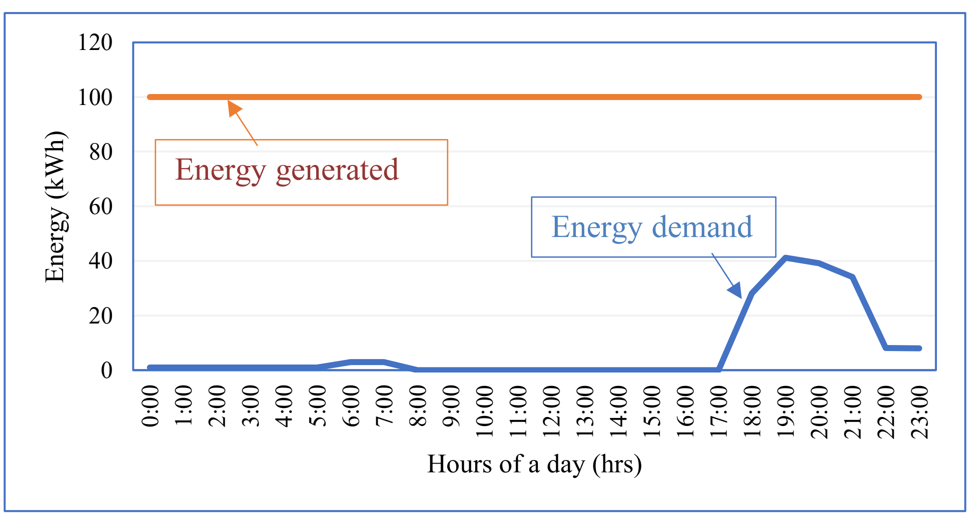

Figure 6: Load vs generation matching analysis.

rise in the evening, reaching a maximum of approximately 43 kWh around 18:00 (only 43% of capacity). Despite this evening peak, the load never exceeds the plant's capacity, indicating that supply is sufficient to meet demand at all times. However, the overall energy demand remains substantially lower than the generation capacity for much of the day, resulting in low utilization of the available power. This underutilization suggests a low load factor and highlights the need for interventions such as promoting daytime productive uses (e.g., agro-processing, irrigation, or refrigeration), implementing battery storage systems to shift surplus energy to peak hours, and introducing demand-side management strategies to optimize energy use and enhance the plant's efficiency and economic sustainability.

Fig. (**7**) shows a ±10% variation in flow (Q), effective head (H), and efficiency (η) in both power output and the NPV of a micro-hydropower plant. Based on Eqn. (1), it can be seen that a ±10% change in any of these parameters leads to a ±10% change in power output and thus proportionally affects NPV. When these variations occur simultaneously, the impact compounds as these effects are multiplicative. Consequently, they lead to potentially altering power and economic returns by over 30%. In the case of +10% variation for all factors, the impact is 1.1^3 or approximately 1.331, and in -10% variation, the impact is 0.9^3 or approximately 0.729. In turn, this leads to about ±33.1% change in power output and NPV. This sensitivity underscores the importance of accurate hydrological and technical assessments in the design phase to ensure financial viability and performance reliability of the project.

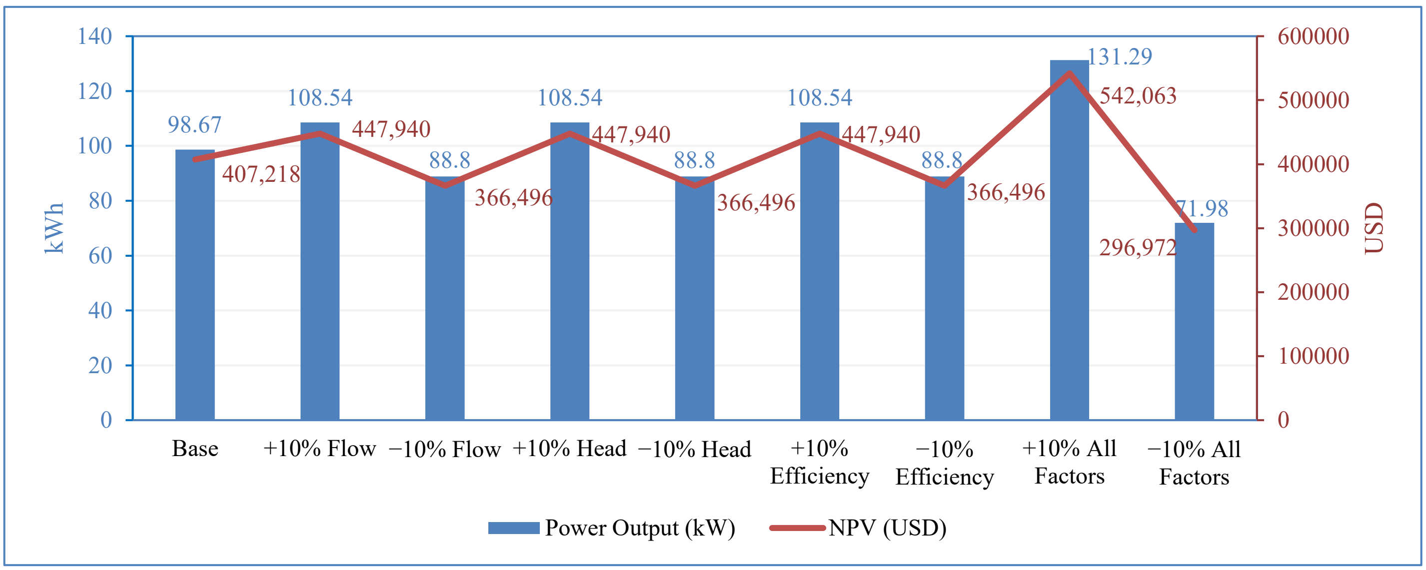

Figure 7: Effects of Q, H, and η variations on the power output (blue color) and NPV (orange color).

5.2. Economic Performance

For the economic evaluation of the proposed hydropower project, an initial investment cost (C_{INV}) of USD 200,000 was considered for a 100-kW run-of-river plant. Based on the expected performance of the system, the plant is projected to generate approximately 876,000 kWh annually. The estimated Levelized Cost of Electricity (LCOE) for the proposed small hydropower plant at Ruhuhu River is approximately USD 0.0417/kWh, based on a 100-kW capacity, an annual generation of 876,000 kWh, and a 10-year project lifespan at a 10% interest rate. This LCOE is substantially lower than the average electricity tariffs in Tanzania, where residential and commercial consumers pay approximately USD 0.084/kWh and USD 0.087/kWh, respectively, under the regulated rates by TANESCO as of 2024–2025 [55] (Table **6**). This suggests a highly competitive cost advantage for the small hydropower plant, especially when compared to the national average LCOE range for hydropower projects in Tanzania, which falls between USD 0.03 and 0.13/kWh depending on scale, location, and financing structure [56]. Furthermore, in off-grid and rural settings, where diesel-based generation costs often exceed USD 0.20/kWh, the proposed plant offers a much more affordable and sustainable alternative [57].

Table 6: Comparison of the LCOE at Ruhuhu River SHPP and other electricity tariffs in Tanzania.

Consumer Sector	Typical Electricity Tariff (USD/kWh)	Reference
Residential (households)	~0.084 USD/kWh (≈ 8.4 ¢/kWh)	[55]
Business (small/medium)	~0.087 USD/kWh (≈ 8.7 ¢/kWh)	[56-57]

To assess the economic viability of the project, a sensitivity analysis was performed by computing the net present value (NPV). As expressed in Equation (7), the NPV is calculated as a function of the projected annual revenue (R_{in}) and the initial investment cost (C_{INV}), discounted over the plant's operational lifespan. Specifically, the analysis considered a 10-year project horizon and annual interest rates of 4 to 10%, reflecting typical financial conditions for energy infrastructure investments in developing contexts.

The cash flow profile is presented in Table **7**. Year zero corresponds to the commencement of the project, during which the capital investment is made. Since no electricity is generated in this initial phase, no revenue is recorded, and the investment cost appears as a negative cash flow. From Year 1 onward, the plant is assumed to operate at full capacity, yielding consistent annual revenue. However, to reflect operational realities such as maintenance and minor outages, the net cash inflow is conservatively estimated at USD 86,120 per year, rather than the full revenue potential. Each year's net cash inflow was discounted to present value terms using the interest rate. The cumulative present value of all future cash flows, minus the initial investment, gives the Net Present Value (NPV) of the project. The effect of the interest rates (4 to 12%) on the NPV of the small hydro power plant at Ruhuhu River is assessed as presented in Table **7**.

Table 7: Estimation of the NPV of a 100-kW hydropower plant at different interest rates.

Year	Cash Inflow (USD)	Present Value (USD) @ 4%	Present Value (USD) @ 6%	Present Value (USD) @ 8%	Present Value (USD) @ 10%	Present Value (USD) @ 12%
0	-200,000	-200,000	-200,000	-200,000	-200,000	-200,000
1	86,120	82,807.69	81,245.28	79,740.74	78,290.91	76,892.86
2	86,120	79,622.78	76,646.49	73,834.02	71,173.55	68,654.34
3	86,120	76,560.37	72,308.01	68,364.83	64,703.23	61,298.51
4	86,120	73,615.74	68,215.11	63,300.77	58,821.12	54,730.82
5	86,120	70,784.36	64,353.87	58,611.82	53,473.74	48,866.80
6	86,120	68,061.89	60,711.20	54,270.21	48,612.49	43,631.07
7	86,120	65,444.12	57,274.72	50,250.19	44,193.18	38,956.31
8	86,120	62,927.04	54,032.75	46,527.96	40,175.62	34,782.42
9	86,120	60,506.77	50,974.30	43,081.44	36,523.29	31,055.74
10	86,120	58,179.59	48,088.96	39,890.22	33,202.99	27,728.34
NPV		498,510.35	433,850.69	377,872.20	329,170.12	286,597.21

The results, summarized in Table **7**, show a clear inverse relationship between the interest rate and the NPV. At a lower interest rate of 4%, the NPV reaches USD 498,510.35, while at 12% it decreases significantly to USD 286,597.21. This trend reflects the diminishing value of future cash flows as the cost of capital increases. In essence, higher interest rates reduce the present value of future revenue streams, thereby lowering the overall economic attractiveness of the project. From a financial standpoint, all tested interest rates yield a positive NPV, suggesting that the project is economically viable under a broad range of capital cost scenarios. This indicates a relatively robust investment opportunity. However, the rate of return diminishes as the interest rate increases, implying that the project's profitability is sensitive to the cost of financing and the perceived investment risk. At 10%, which is often considered a benchmark for energy infrastructure investments in developing countries, the NPV stands at USD 329,170.12. This value supports the conclusion that the project remains financially sound even when evaluated against conservative financial assumptions. The NPVs at 8% (USD 377,872.20) and 6% (USD 433,850.69) further highlight the project's potential for higher profitability under more favorable financing conditions. Notably, the NPV at 4% indicates a strong return on investment, which may be applicable in contexts where concessional loans or climate finance mechanisms are available. Conversely, the reduced NPV at 12% underscores the importance of securing low-interest financing to maintain economic viability, particularly in rural electrification and development-focused energy projects.

The IRR, estimated at approximately 25.5%, is well above commonly used benchmark discount rates such as 10% or 12%, indicating that the project would remain profitable under a wide range of financing scenarios. A high IRR suggests that the investment generates returns significantly greater than the cost of capital, which is critical for attracting both public and private investors, especially in emerging markets where capital is often constrained. On the other side, the simple payback period calculated at just 2.32 years further emphasizes the attractiveness of the project by showing that the initial investment of USD 200,000 is recovered in a relatively short period. In capital-intensive infrastructure projects like hydropower, a payback period of less than 3 years is considered highly favorable, especially when aligned with a projected operational life of 20–30 years. This short recovery period implies reduced investment risk and enhances liquidity for the investor. In terms of return on investment (ROI), the plant reveals a return of about 330.6% over the 10 years, confirming the substantial profitability. This high ROI indicates that the project generates over three times the initial capital investment in net gains, reflecting strong operational efficiency and cost-effectiveness. In addition, the profitability index (PI) of 2.49 at 4% interest rate up to 1.43 at a 12% interest rate provides further evidence of the plant's economic soundness. A PI greater than 1 implies that the project adds value, and a value of 2.49 means that for every dollar invested, the project yields USD 2.49 in present value of future cash flows. This makes the project not only viable but also competitive compared to alternative renewable or conventional energy investments. Collectively, these indicators reflect a strong financial case for the development of small hydropower in the region. The robustness of the project under varying discount rates, confirmed through sensitivity analysis, further enhances its credibility.

6. Conclusion

This study evaluated the techno-economic assessment of a run-of-river micro hydropower plant for rural electrification through Ruhuhu River in Njombe region, Tanzania. The study performed a detailed hydrological assessment of the available water resources in Mavanga village to determine the potential for micro-hydropower generation. The assessment led to the determination of hydropower generation from the river. Furthermore, the study executed the civil design and later economic assessment to understand the viability of the project. The outcomes revealed the water flow rate of 71.8 m^3/s, power generation of 98.67 kW, and generator specific speed of about 434.22 rpm, which matches a Kaplan turbine. In civil structure, the mean velocity flow at the inlet is determined to be 1.162 m/s for a trash rack with a flow area of 3.68 m^2 and a flow rate of 4.28 m^3/s. Also, the penstock thickness and inner diameter of 2.4 mm and 20.8 cm were found to suit the design. In terms of economy, the investment cost was found to reach USD 200,000, with the net present value (NPV) of USD 529,170.12. The small hydropower plant demonstrates strong financial viability, with an IRR of 25.5%, far above typical discount rates, and a payback period of just 2.32 years, indicating rapid capital recovery. A ROI of 330.6% and a profitability index of 2.49 further confirm its high profitability and investment appeal. The low LCOE, combined with the project's positive NPV and favorable sensitivity outcomes, underscores the viability of small-scale hydropower investments in Tanzania's rural electrification and energy transition efforts. These results will contribute to evidence-based decision making, inspire renewable energy penetration, and support the growth of inclusive and sustainable energy systems in rural communities.

7. Recommendation

Future studies are recommended to incorporate detailed economic assessment and sensitivity analysis, and socio-environmental assessment to understand the socio-economy-environmental benefits to society. This will help to understand the social perception of micro hydroelectricity for driving socio-economic activities. The findings could be key in the formulation of renewable energy policy for rural electrification. Moreover, these results could awaken the government of Tanzania to realize that small hydropower is a renewable energy source for increasing electricity access, especially in rural areas. Furthermore, policymakers and decision makers could focus on making micro hydropower electricity more favorable in investment and unit cost as well especially in remote areas, making it competitive and attracting more investors.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

Author Contributions

Abbas Issa: Conceptualization, Methodology, Software, Investigation, Validation, Writing - original draft, Pius Victor Chombo: Conceptualization, Methodology, Software, Investigation, Writing - review & editing. Gerutu Bosinge Gerutu, Oscar Andrew Zongo, Kenedy Greyson Aliila: Writing - original draft, Writing - review & editing. Ramadhani Omari Kivugo: Writing – review.

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Appendix

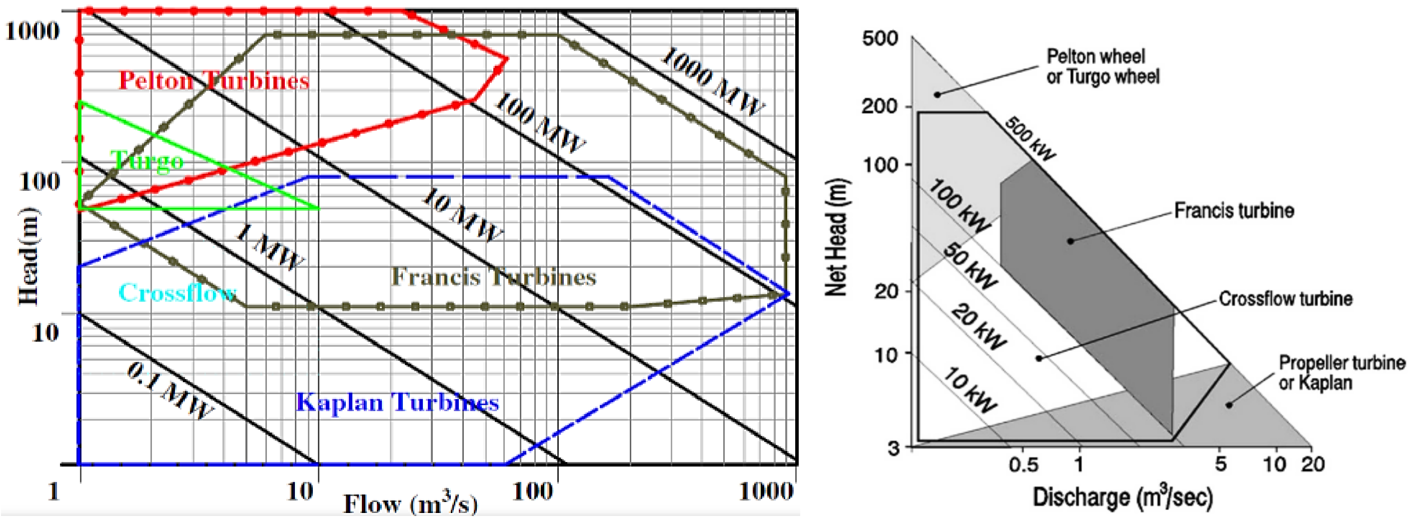

Figure A1: Hydro turbine selection chart [35, 39, 48].