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Technical Feasibility Reassessment of Hydropower Development on Mada River for Rural Electrification in Nasarawa State, Nigeria

Maduka, Fidelia I., Obodoh, Dominic A., Okongwu Michael A.

Department of Building, Faculty of Environmental Sciences, Nnamdi Azikiwe University, Awka. Nigeria.

Abstract

Electricity plays a crucial role in a nation's socioeconomic development. Despite its importance, access to reliable and sustainable electricity remains grossly inadequate in many rural settlements in Nigeria. The seven-household settlement along Mada River is not connected to the national grid and depends mainly on diesel generators. Although a previously installed 5 kW hydrokinetic system is no longer operational, selecting a suitable replacement requires reassessing the site. This study reassesses the technical feasibility of hydropower development on the Mada River for rural electrification in an off-grid rural settlement in Nasarawa State, Nigeria. The study achieved this by setting the following objectives and methods: conducting field measurements of available head with a hand GPS and assessing river flow using the velocity–area method. The findings include a gross head of 2.00 m and discharge of 0.78 m^3/s resulting in a theoretical hydropower potential of 15.29 kW; the electricity demand analysis gave a projected demand of 4. 393 kW, which informed the selection of a 5 kW plant capacity; the turbine design flow was determined as 0.340 m^3/s, and the selection of a 600 mm internal-diameter HDPE penstock resulted in an estimated net head of 1.753 m; the study selected a run-of-river scheme with a propeller turbine, with an estimated output of 4.385 kW. Estimates show that the technical potential of 4.385 kW exceeds the settlement's current peak demand of 3.14 kW. The findings indicate preliminary technical potential for hydropower generation to support the settlement's basic electricity needs. However, sustainable electricity supply still requires further verification of the available head, seasonal river flow, and system performance. Periodic assessment of future electricity demand, detailed hydraulic design (including flood protection and structural anchoring), and economic and environmental impact assessment are recommended before implementation.

Keywords: Mada River, Head Measurement, Discharge Measurement, Penstock Design, Hydropower Potential, Technical Feasibility Assessment, Scheme Selection, Design Flow.

1. Introduction

Electricity plays an important role in socioeconomic development by supporting productive activities and essential services. Moss and Kincer (2023) state that "Nowhere in the world is there a wealthy country that consumes only a little energy, nor a poor country that consumes a lot." Despite its importance, access to a reliable supply remains a major challenge in Nigeria. According to the National Bureau of Statistics (NBS) (2024), 92 million Nigerians are without access to the national

grid, particularly in rural settlements. Many rural households depend on diesel generators, kerosene lamps and other alternatives that may be costly, unreliable and environmentally harmful (Alliance for Renewable Electrification [ARE], 2024). Therefore, the rural settlements need an alternative renewable energy solution.

Hydropower offers a renewable solution to address rural electricity deficits by providing a reliable, low-cost, and environmentally sustainable energy source. It is one of the most promising options for rural electrification (U.S. Department of Energy, 2022). Hydropower generation converts the energy of flowing water into electrical energy through turbines and generators (Ratlamwala and Dincer, 2018). The amount of electricity that can be generated depends principally on the available river discharge and head. These characteristics determine hydropower potential and inform the system capacity that may be installed at a particular site (Isyaku, 2014). However, hydropower development may also have environmental effects. The Nation (2014) reported that the abandoned 30 kW Mgbowo hydropower project in Enugu State led to water pollution, loss of aquatic life, and safety concerns for local fishermen, underscoring the importance of environmental impact assessment during detailed project planning.

The Mada River in Nasarawa State borders an off-grid rural settlement of seven households that rely primarily on diesel generators. A 5 kW hydrokinetic turbine previously installed in the river was reportedly dislodged from its anchor and swept downstream during high flow. This failure highlights the need to reassess the river's hydropower potential and identify a suitable alternative scheme. Such reassessment requires field measurements of river discharge and available head, electricity demand assessment, preliminary penstock design and turbine selection. Comparing the estimated technical hydropower potential with the settlement's electricity demand provides a basis for selecting a suitable hydropower scheme.

Previous studies have examined river discharge, hydraulic head, electricity demand and preliminary hydropower design. Otuagoma et al. (2015, 2016) measured river discharge and hydraulic head, while Oladeji and Akorede (2018) developed a method for estimating rural electricity demand. Chinyere et al. (2017) combined hydropower assessment, electricity demand estimation, and preliminary system design, although the penstock analysis focused mainly on diameter and length. Similarly, Michael and Jawahar (2017) integrated hydropower and demand assessments but relied on assumed household appliance quantities and ratings. Abdullahi et al. (2017) investigated the feasibility of integrating a photovoltaic system or grid electricity with the previously installed 5 kW hydropower system at Mada-Gudi Community using secondary data and HOMER software. This study builds on these previous studies by conducting direct field measurements of river discharge and available head, reassessing electricity demand, and performing a preliminary penstock design using site-specific data to support the selection of a suitable alternative hydropower scheme and turbine. This preliminary technical reassessment provides a site-specific methodological reference for similar low-head hydropower assessments. Economic feasibility and overall project viability remain outside its scope.

This study reassessed the technical feasibility of hydropower to identify a suitable alternative scheme for providing electricity for basic building services in an off-grid rural settlement in Nasarawa State, Nigeria. The reassessment integrated field measurements of available head and river discharge,

turbine design flow determination, appliance-based electricity demand assessment, and preliminary penstock design to select a suitable alternative hydropower scheme and turbine type. This study could provide technical data to support considering Mada River hydropower as an alternative to diesel-generated electricity in the settlement.

2.0 Materials and Methods

2.1 Study Area

The study was conducted on the Mada River near Gudi in Akwanga Local Government Area, Nasarawa State, Nigeria. The geographical setting of the study area is illustrated in Figures 1 - 3. Mada River is situated in a rural area near the Akwanga Water Board and is accessible via the Akwanga–Lafia Road. The wider Mada River watershed lies entirely within Nigeria and extends across Kaduna, Plateau and Nasarawa State, covering approximately 4,450 km². (Nasarawa Geographic Information Service (Global watersheds, 2026). The study area experiences its dry season from November-March and a rainy season from April–October.

The study area has seven (7) households and a church, whose primary livelihoods are farming and fishing. Other public services, such as schools, health centers, markets and rural banks, are largely absent; this shows the community's need for reliable electricity and basic services.

Data Collection

The researcher collected primary data directly from the field to obtain information on the river characteristics, site conditions, and electricity demand within the study area. Rainfall, topographical, other hydrological and land-use data were obtained from the Nigerian Meteorological Agency (NiMet), the Nasarawa Geographic Information System Office (NAGIS) and Global watersheds, (2026), respectively.



Figure 1. Map of Nigeria showing Nasarawa State



Figure 2 Map of Nasarawa State showing Akwanga L.G.A

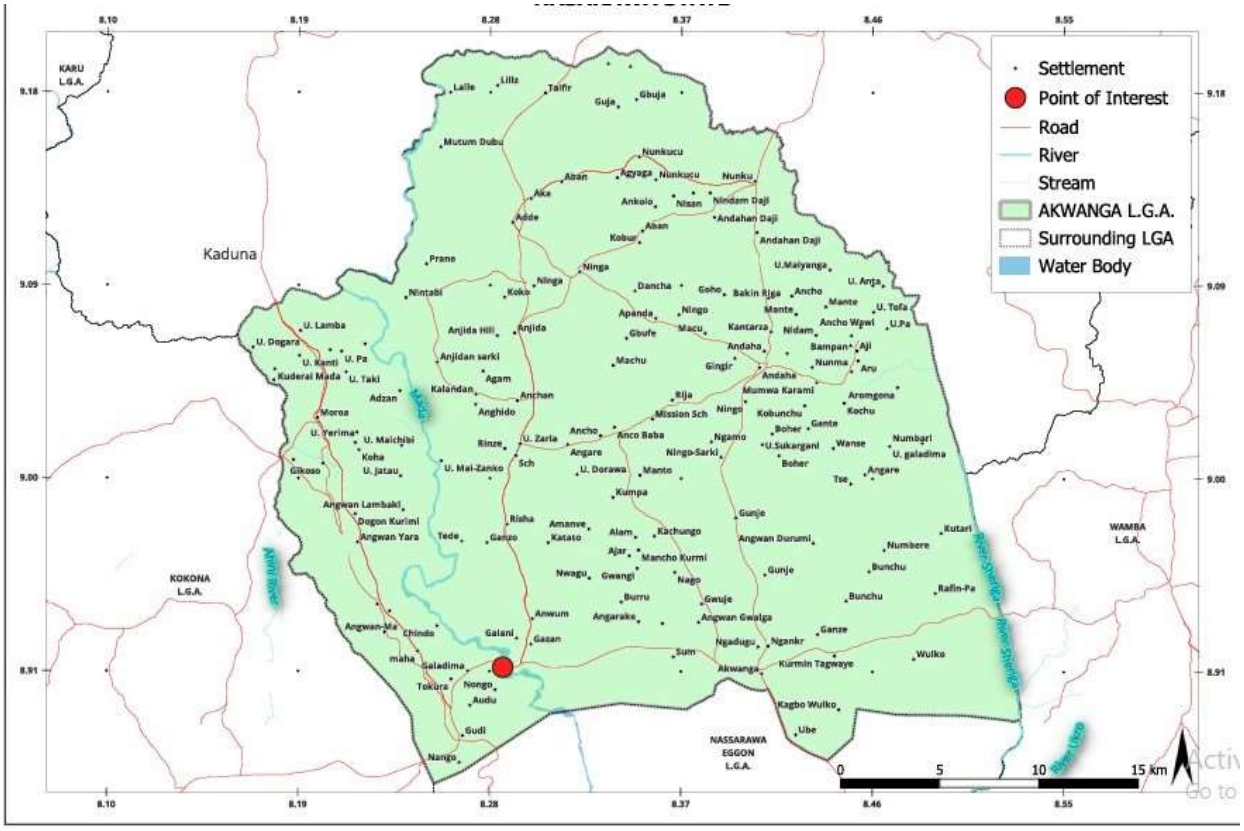


Figure 3. Map of Akwanga showing Mada River

2.3 Methods

2.3.1 River Discharge Measurement

The river discharge (m^3/s) was measured in January 2026, during the dry season, using the velocity-area method. The result reflects the river flow conditions at the time of the field measurement and was used to estimate the theoretical hydropower potential of the Mada River.

2.3.1.1 Velocity-area method

A relatively straight section of the river with uniform flow was selected for the measurement. The width of the selected river section was measured and divided into equal segments, and the water depth at each interval across the section was measured. Figure 4 illustrates the division of the river cross-section and the measurement of depth at equal intervals.

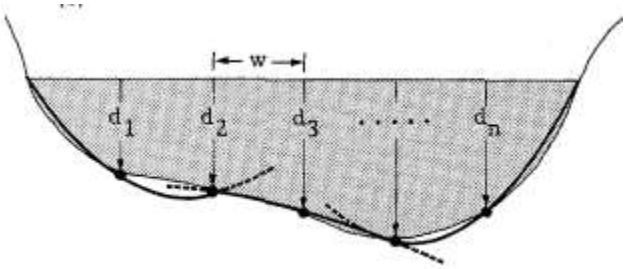


Figure 4. Illustration of River Cross-Section Measurement
Source: (MHP Source Book, Inversin, 1986)

Appropriate geometric formulas for a triangle and a trapezium in equation (1) were used to calculate the area of each section.

$$\mathbf{a_1} = \boldsymbol{w\,X}\ \frac{(\boldsymbol{d1})}{\mathbf{2}};\ \mathbf{a_2} = w\ x\ \frac{(\boldsymbol{d1+d2})}{\mathbf{2}};\ \mathbf{a_3} = w\ x\ \frac{(\boldsymbol{d2+d3})}{\mathbf{2}};\ a_n = w\ X\ \frac{(dn)}{2} \qquad (1)$$

At the same relatively straight river section selected for the cross-sectional area measurement, the flow velocity was measured. The surveyor marked a known distance, D, along the flow direction, released a float at the upstream end of the measured distance, and recorded the time taken to travel the known distance using a stopwatch. Equations (2) and (3) were used to calculate the surface velocity at each segment.

$$Vi_i = \frac{D}{ti} \qquad (2)$$

The measured velocity was adjusted using a correction factor of 0.85 to obtain the average velocity as:

$$\tilde{V} = Vs \times 0.85 \qquad (3)$$

The continuity equation (4) was then used to calculate the river discharge.

$$\text{Total Discharge } Q = \sum AV \qquad (4)$$

2.3.2 Available Head Measurement

The gross hydraulic head was determined using a hand-held GPS device. A surveyor measured and recorded the coordinates and elevations of the proposed intake and tailrace points during the site measurement; the gross head (Hg) was calculated as the difference between the elevations of the two points using equation (5):

$$Hg = E1 - E2 \qquad (5)$$

Using the recorded UTM Easting and Northing coordinates, the horizontal distance between the intake and tailrace points was calculated using the two-point distance equation:

$$L = \sqrt{[(Et - Ei)^2 + (Nt - Ni)^2]} \qquad (6)$$

2.3.3 Theoretical Hydropower Estimation

The theoretical power potential available from the River Mada was calculated using the gross head and the measured discharge by the standard power equation:

$$P = 9.8QHg \qquad (7)$$

2.3.4 Electricity Demand Assessment

The electricity demand survey was carried out by interviewing representatives of the seven households and the place of worship face-to-face, and the results were analyzed using a bottom-up, appliance-based approach. The power rating of each appliance was based on standard appliance ratings, and each building's connected load was calculated as follows:

$$P_{connected} = \sum (Ni \times Wi) \qquad (8)$$

Where Ni is the number of appliances of type i and Wi is the power rating of appliance type i, in watts (W).

A diversity factor of 1.2 was adopted from ICIMOD (1998) to account for variations in non-simultaneous electricity use. The peak electricity demand was estimated by applying the diversity factor (DF) to account for non-simultaneous appliance use, as follows.

$$P_{peak} = \frac{\text{Total connected Load}}{DF} \quad (9)$$

The estimated peak load was projected by applying a 40% growth allowance to account for possible future increases in appliance ownership and electricity consumption. This approach is consistent with the Micro-Hydropower System Design Guideline (2020), which incorporates an allowance for future load growth. The 40% allowance represents a preliminary planning assumption without a specified projection period. The projected electricity demand forms the basis for selecting the hydropower plant capacity. Because this study was a preliminary technical feasibility assessment, it did not evaluate detailed daily load profiles or seasonal variations in electricity demand.

2.3.5 Determination of Design Flow

The discharge required to generate the selected plant capacity (p) was calculated using the hydropower equation, with an overall efficiency of 0.75 and an available head of 2.00 m.

$$Q_{requried} = \frac{P}{\eta \rho g Hg} \quad (10)$$

The calculated required discharge was compared with the results of the Flow Duration Curve (FDC) analysis conducted as part of the broader thesis research to select the design flow. The FDC was developed using eleven years of rainfall data (2015-2025), with monthly discharge estimated using a rainfall-runoff method and adjusted using the Mada River's field-measured discharge of January 2026. Detailed FDC analysis is not within the scope of this article.

The river flow was estimated by subtracting the selected design flow from the minimum river discharge using:

$$Q_r = Q_{min} - Q_d \quad (11)$$

2.3.6 Preliminary Penstock Design and Net Head Determination

2.3.6.1 *Selection of penstock material*

The penstock material was selected based on its suitability for the available head and design flow, corrosion resistance, ease of installation, durability and availability. Table 1 presents the mechanical properties and Manning's roughness coefficients of commonly used penstock materials.

Table 1 Mechanical Properties and Manning's Roughness Coefficients of Common Penstock Materials.

Material	Young's modulus of elasticity E (N/m²)E9	Coefficient of linear expansion a (m/m °C)E6	Ultimate tensile strength (N/m²)E6	n
Welded steel	206	12	400	0.012
Polyethylene	0.55	140	5	0.009
Polyvinyl chloride (PVC)	2.75	54	13	0.009
Asbestos cement	n.a	8.1	n.a	0.011
Cast iron	78.5	10	140	0.014
Ductile iron	16.7	11	340	0.015

Source: MHP source Book

2.3.6.2 *Penstock diameter*

The economic internal diameter was estimated using the Manning-based equation presented by ESHA (2004):

$$D = 2.69 \left[\frac{n^2 Q^2 L}{H}\right]^{0.1875} \quad (12)$$

Where, D = economic diameter of the penstock (m), n= Manning Roughness Coefficient, Q = discharge flow (m3/s), L = total length of penstock in (m) and H_g = gross head (m). The suitability of the selected pipe diameter was assessed by calculating the corresponding flow velocity given by:

$$\text{Velocity} = \frac{Q}{\frac{\pi}{4} x\, D^2} \quad (13)$$

2.3.6.3 *Penstock wall thickness and water hammer assessment*

The penstock wall thickness was determined by considering the internal pressure resulting from the gross head and transient pressure associated with changes in water velocity. The assessment followed the preliminary water-hammer analysis procedure described by ESHA (2004), considering the penstock's hydraulic characteristics, pressure-wave velocity, critical closure time, surge head, and corresponding internal pressure. The water velocity in the pipe is calculated using Equation (13). A preliminary water hammer analysis was carried out to assess the additional pressure resulting from sudden or gradual flow interruption.

The pressure wave velocity was estimated based on the elasticity of the water and pipe material according to the formula:

$$C = \sqrt{\frac{k}{[1+\frac{KD}{Et}]\rho}} \quad (14)$$

Where c = pressure wave velocity (m/s), k = bulk modulus of water $2.1x10^9$ Pa, E = modulus of elasticity of HDPE (Pa), t = wall thickness (m)

For rapid closure, the increase in pressure of the water column, due to the pressure wave, is:

$$P = c\,\frac{\Delta v}{g} \quad (15)$$

Where Δv = change in velocity

The total pressure head was estimated as:

$$Htotal = Hg + \Delta H \quad (16)$$

Where Hg is the gross head (m) and ΔH is the estimated surge head (m).

The internal design pressure was obtained from:

$$P = \rho g Htotal \quad (17)$$

Where: ρ = density of water (kg/m³); g = acceleration due to gravity (m/s²) and Htotal = total pressure head, including the surge allowance (m).

The required penstock wall thickness was determined to ensure that the pipe could safely withstand the internal water pressure during operation. The required wall thickness was determined using the thin-cylinder equation.

$$e = \frac{PxD}{2X\sigma} \quad (18)$$

Where, t = pipe wall thickness (m), P = internal pressure including surge allowance (Pa), D = penstock diameter (m), $\boldsymbol{\sigma}$ = allowable stress of the penstock material

2.3.6.4 Safety factor

The safety factor was determined to verify that the penstock material's strength and effective wall thickness were adequate to withstand the maximum internal pressure, including the surge allowance. It was calculated using the equation presented by ICIMOD (2002):

$$SF = \frac{t\ effective\ x\ S}{5\ X\ h\ total\ x\ 10^3 x\ d} \quad (19)$$

Where: S = ultimate tensile strength of the pipe material in N/m^2; D = internal diameter of the pipe in m; t_e = effective wall thickness of the penstock (m).

The calculated safety factor was compared with the recommended value for the selected penstock material. If SF < 3.5, the penstock thickness would be recalculated until SF > 3.5 (ICIMOD, 2002).

2.3.6.5 *Penstock head losses and net head*

The major head loss because of friction along the penstock was estimated using the Manning equation recommended by ESHA (2004):

$$h_f = \frac{10.3\ n^2 Q^2 L}{D^{5.333}} \quad (20)$$

Where, hf = friction head loss (m); L = penstock length (m); n = Manning roughness coefficient; Q = design discharge (m³/s); D = penstock diameter (m).

The minor head losses due to turbulence at the entrance, bends, valves, joints, contractions and other fittings were estimated as:

$$h_m = K\frac{V^2}{2g} \quad (21)$$

Where ∑K = summation of the dimensionless experimental coefficient; V = flow velocity in the penstock (m/s); h_m = total minor head loss and g = acceleration due to gravity (m/s²).

The total head loss was obtained as:

$$hL = hf + hm \quad (22)$$

The estimated major and minor losses in the penstock were deducted from the gross head to obtain the net head available for turbine selection and power estimation.

2.3.7 Technical Hydropower Potential of Mada River

Using design flow, net head and overall efficiency of 75%, the technical hydropower power potential was calculated using the standard power equation.

$$P = \eta \times \rho \times g \times h \times Q \quad (23)$$

Where, P = Power (W), η = efficiency, ρ = density of water (1000 kg/m3), g = acceleration due to gravity (9.81 m/s2), h= net hydraulic head (m) and Q= design flow(m^3/s).

The estimated technical hydropower potential represents the portion of the theoretical potential that can be realistically generated, considering the selected design flow, hydraulic head losses in the penstock, and overall system efficiency. The technical hydropower potential was compared with the projected electricity demand to assess whether it can meet the study settlement's basic electricity demand. It was further compared with the proposed plant capacity to assess the suitability of the selected capacity. The hydropower scheme was classified based on the available head, adopted plant capacity and the mode of operation, as shown in Tables 2 and 3.

Table 2. Hydropower Classification by Head

Category	Head Range
Low head	2–30m
Medium head	30–100m
High head	≥ 100m

Source: Energy Commission of Nigeria (ECN), (2022)

Table 3. Classification of Hydropower Schemes Based on Capacity

Category	Installed Capacity
Pico hydropower (PHP)	<5Kw
Micro hydropower (MHP)	<500kW
Mini hydropower (MHPP)	500kW-1MW
Small hydropower (SHP)	1MW – 30MW
Medium hydropower (MeHP)	30MW – 100MW
Large hydropower (LHP)	>100MW

Source: ***ECN* (2022)**

2.3.8 Turbine selection

The turbine for the proposed hydropower scheme was selected based on the net head, design flow, technical hydropower potential and turbine rotational speed. The turbine specific speed was calculated using equation (24) as given by (Inversin, 1986) NRECA, Int. Found:

$$N_s = \frac{N\sqrt{P}}{H^5/4} \quad (24)$$

Where, Ns = specific speed, N = working speed of turbine (rev/min), P = maximum turbine output (kW), H = net head (m).

Table 4. Specific Speed Ranges for Various Types of Turbines

Type of runner	N_s
Pelton	12-30
Turgo	20-70
Crossflow	20-80
Francis	80-400
Propeller and Kaplan	340-1000

Source: (Inversin, 1986) MHP Source Book

2.3.8 Sensitivity Analysis

A sensitivity analysis was conducted to assess the effects of variations in design flow, penstock diameter and overall efficiency on the estimated technical hydropower potential. Design flow and overall efficiency were independently varied by ±15% from their baseline values of 0.340 m^3/s and 75%, respectively. Penstock diameters of 500 mm, 600 mm and 700 mm were also evaluated. The penstock length was maintained at 138 m. For each variation in flow or diameter, major and minor head losses and the corresponding net head were recalculated using Equations (20)–(22). The resulting technical hydropower potential was determined using Equation (23). A combined adverse scenario involving simultaneous 15% reductions in design flow and overall efficiency was also evaluated. These variations were treated as illustrative scenarios rather than measured uncertainties.

3. Results and Discussion

3.1 River Discharge and Gross Head Measurement

Equations (1) to (4) were used to estimate the Mada River discharge (m^3/s), and the available gross head between the proposed upstream and downstream points was estimated using Equations (5) to (6). The results are presented in Tables 3 and 4, respectively.

Table 5. Results of the Cross-Sectional Area, Flow Velocity and River Discharge

Subsection	Partial Area (m^2)	Average Velocity, v = m/s	Discharge Q = av (m^3/s)
1	0.4418	0.2516	0.1112
2	0.9263	0.2975	0.2756
3	0.9975	0.2661	0.2654
4	0.5130	0.2397	0.1230
Total			**0.7752**

Table 6. Coordinates, Elevations and Head Measurement Results

Parameter	Upstream Point (E1)	Downstream (E2)
Latitude	8°54'47"N	8°54′43″ N
Longitude	8°17' 10"E	8°17′08″ E
Elevations (m)	400	398
Gross head (E1 – E2) (m)		2
Horizontal distance (m)		138

3.2 Theoretical Hydropower Potential Result

The measured discharge of 0.78 m^3/s and gross head of 2.00 m yielded a theoretical hydropower potential of 15.29 kW, indicating preliminary potential of Mada River for electricity generation despite its low head. However, the estimated 15.29 kW represents theoretical, not technical, potential, as hydraulic losses and turbine-generator inefficiencies reduce available power. Also, a single lean-season discharge measurement does not establish year-round flow availability, so determining the design flow and assessing hydraulic losses are necessary for a more realistic estimate of the available hydropower potential.

3.3 Electricity Demand Assessment

The community's electricity demand was determined from the electrical appliances identified in the seven households and the communal building. Table 5 summarizes the estimated total connected load, present peak demand, future-growth allowance, projected demand, and adopted plant capacity.

Table 7. Summary of the Electricity Demand Assessment Results

Parameter	Outcome
Seven households' electricity demand	2.810Kw
One church	0.955Kw
Total connected load	3.765Kw
Diversity factor	1.2
Present peak demand	3.138Kw
Future electricity demand allowance	40%
Projected electricity demand	4.393Kw
Selected standard plant capacity.	5.0Kw

The load survey results in Table 5 show an estimated peak electricity demand of 3.138 kW for the seven households. Applying a 40% future growth allowance increased the projected demand to 4.39 kW, leading to the selection of a 5 kW plant capacity. This aligns with Oladeji and Akorede (2018) in Nigeria and Michael and Jawahar (2017) in India, who applied appliance-based electricity demand assessment to rural electrification planning. The selected capacity meets estimated present demand and future growth while avoiding excessive plant sizing. Although the 5 kW capacity is below the theoretical hydropower potential of 15.29 kW, its suitability depends on the available technical hydropower potential after accounting for design flow, hydraulic losses and system efficiencies.

3.3 Determination of Design Flow

The discharge required to generate the selected 5.0 kW power output was calculated using the hydropower equation (10), with an overall efficiency of 0.75 and an available head of 2.00 m. The required discharge was estimated to be 0.340 m^3/s.

The results of the FDC analysis using an estimated river discharge derived from rainfall-runoff analysis of eleven (11) years rainfall data of the Mada River are presented in Table 6.

Table 8. Presents a Summary of Flow Duration Curve (FDC) Using an Estimated River Discharge for Mada River (2015 -2025)

Parameter	Q_{90}	Q75	Q50	Q_{min}
Value (m^3/s)	**1.72**	**4.77**	**56.91**	**0.87**

The FDC analysis showed variations in river discharge between the wet and dry seasons, with an estimated minimum discharge of 0.78 m^3/s.

Inversin (1986) states that "For a single-turbine run-of-river scheme operating with less than the annual minimum streamflow, the required flow may be used as the turbine design flow". Because the required flow of 0.340 m^3/s was lower than the estimated minimum discharge of 0.78 m^3/s, 0.340 m^3/s was selected as the turbine design flow for the proposed 5.0 kW plant. This leaves a residual flow of 0.440 m^3/s to avoid damage to aquatic life in the river. This is in line with ESHA (2004) recommended 0.5% of minimum flow as residual flow. Also, Temel et al. (2023) highlighted the importance of

maintaining downstream flow in run-of-river hydropower development. However, the adequacy of the residual flow for ecological requirements and the year-round reliability of the estimated discharge require further assessment.

3.4 Results of Preliminary Penstock Design

The preliminary penstock design, including penstock diameter selection, hydraulic head losses, transient pressure analysis, wall thickness determination, and factor of safety verification, was carried out using Equations 12-22. The results are presented in Table (7)

Table 9. Results of Preliminary Penstock Design

Design Parameter	Design Result	Unit
Penstock material	HDPE	-
Penstock length	138	M
Design flow	0.340	m^3/s
Flow velocity	1.203	m/s
Internal diameter	600	mm
Goss head	2.0	m
Total hydraulic head loss	0.247	m
Net head	1.753	m
Pressure-wave velocity	95.53	m/s
Rapid closure surge head	11.69	m
Total pressure head	13.69	m
Internal Pressure	134.30	kPa
Calculated wall thickness	29.20	mm
Adopted wall thickness'	30.00	mm
Calculated Safety factor	3.55	

Selecting a 600 mm HDPE penstock provides a relatively low flow velocity, which helps limit hydraulic losses under the low-head conditions of the Mada River. Obinna Ajala Chinyere et al. (2017), in their penstock design for the Kuchigoro Small Hydro Project in Nigeria, similarly emphasized the importance of selecting an appropriate diameter to reduce hydraulic losses. However, while their study achieved a head loss of 2.5%, the present study recorded 12.4%, indicating a greater proportion of the available head lost during water conveyance. This difference highlights the sensitivity of low-head hydropower schemes to hydraulic losses and the importance of careful penstock sizing.

The transient pressure assessment further demonstrates that water hammer can produce substantial pressure increases even in low-head schemes. This agrees with Obinna Ajala Chinyere et al. (2017), who considered pressure wave velocity, surge head and safety factor in their penstock design. The preliminary wall-thickness assessment therefore provides an important basis for evaluating the structural requirements of the proposed HDPE penstock.

3.5 Hydropower Scheme and Turbine Type Selection

The hydropower scheme was classified and selected based on available head, plant capacity and mode of operation as presented in Tables 2 and 3, and the selection of the turbine type was based on the specific speed ranges shown in Table 4.

Table 10. Results of Hydropower Scheme and Turbine Selection.

Selection Criterion	Result
Available net head	1.753 m
Design flow	0.340 m^3/s
Technical hydropower potential	4.385 kW
Proposed plant capacity	5.0 Kw
Head classification	Low head
Capacity classification	Micro-hydropower
Mode of operation	Run-of-river
Turbine specific speed	395.07 rpm
Selected turbine type	Propeller turbine

The results presented in Table 8 classify the proposed hydropower scheme as a low-head, run-of-river micro-hydropower system, based on the available net head of 1.753 m, proposed plant capacity of 5.0 kW and mode of operation. The run-of-river configuration was selected to use the Mada River's natural flow without constructing a dam or storage reservoir. Unlike the previous hydrokinetic installation, which operated directly with the river flow, the proposed scheme would convey water through a penstock to a turbine installed in a powerhouse. The calculated specific speed of 395.07 rpm falls within the range specified for propeller turbines, so a propeller turbine was selected. The estimated technical hydropower potential of 4.385 kW was lower than the theoretical potential of 15.29 kW due to the selected design flow, hydraulic head losses and system efficiency. Nevertheless, the estimated technical potential approximately meets the settlement's projected electricity demand of 4.393 kW, supporting the preliminary suitability of the proposed scheme to meet the settlement's current peak demand 0f 3.138kW. However, the small margin between estimated generation and projected demand does not ensure the scheme can reliably meet electricity demand throughout the year as the settlement expands. Abdullahi et al. (2017) evaluated alternative electricity supply configurations for the previous 5 kW hydropower installation at Mada-Gudi and identified a hydro–diesel–battery system as the preferred off-grid configuration. Although they considered solar photovoltaic integration, they did not include it in their reported optimal configurations. Their findings highlight the potential of hybrid systems as alternative electricity supply options.

3.6 Sensitivity Analysis and Technical Hydropower Output

Table 9 shows the effects of variation in design flow, penstock diameter and overall efficiency on the estimated technical hydropower potential, including a combined adverse operating scenario.

Table 11: Sensitivity Analysis of Technical Hydropower Potential

Scenario	Design flow (m^3/s)	Pipe Diameter (mm)	Total Head Loss (m)	Net head (m)	Efficiency (%)	Technical Power Potential (kW)
Baseline	0.340	600	0.247	1.753	75.00	4.385
Flow -15%	0.289	600	0.179	1.821	75.00	3.873
Flow +15%	0.391	600	0.327	1.673	75.00	4.813
Diameter 500mm	0.340	500	0.628	1.372	75.00	3.432
Diameter 700mm	0.340	700	0.113	1.887	75.00	4.720
Efficiency - 15%	0.340	600	0.247	1.753	63.75	3.727
Efficiency + 15%	0.340	600	0.247	1.753	86.25	5.043

The sensitivity analysis showed that variations in design flow, penstock diameter and overall efficiency influenced the estimated technical hydropower potential. A 15% reduction in flow decreased the estimated power output from 4.385 kW to 3.873 kW, while a 15% increase raised it to 4.813 kW, accounting for changes in hydraulic losses and net head. Reducing the penstock diameter from 600 mm to 500 mm increased hydraulic losses and decreased power output to 3.432 kW, whereas increasing it to 700 mm reduced hydraulic losses and increased output to 4.720 kW. Similarly, a 15% reduction in flow and a 15% increase in overall efficiency resulted in power outputs of 3.727 kW and 5.043 kW, respectively, without affecting hydraulic losses. The combined adverse scenario, representing simultaneous 15% reductions in flow and efficiency, reduced the estimated technical hydropower potential to 3.292 kW. These findings indicate that the proposed scheme may not consistently meet the projected electricity demand of 4.39 kW under less favorable operating conditions, highlighting the need for further hydrological monitoring and hydraulic design verification before implementation.

4.0 Conclusion and Recommendation

The technical reassessment of Mada River indicates preliminary hydropower potential to support the off-grid settlement's basic residential and communal electricity demand in Nasarawa State, Nigeria. Based on the assessment of theoretical and technical hydropower potential, electricity demand

and preliminary penstock design parameters, the study identified a low-head, run-of-river micro-hydropower scheme with a propeller turbine as a suitable alternative to the previously installed 5kW hydrokinetic system. Unlike the previous 5kW hydrokinetic turbine installed directly in the river flow, which was reportedly washed away during a period of high river flow, the run-of-river scheme would convey water through an anchored penstock to a propeller turbine in a powerhouse located outside the river channel, reducing exposure to high flow and floating debris.

The study demonstrated a systematic approach to preliminary hydraulic design and to selecting the hydropower scheme and turbine. Although the estimated technical power output of 4.385 kW approximately matches the settlement's projected electricity demand of 4.393 kW, sustainable electricity supply cannot be confirmed due to hydrological, hydraulic and demand uncertainties. The sensitivity analysis further showed that variations in these parameters affect the estimated technical hydropower potential. Further verification of these parameters, detailed hydraulic design (including flood protection and structural anchoring), and economic and environmental impact assessment are recommended before implementation.

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