

PAPER 34 – ASSESSING THE FEASIBILITY OF EXPLOITING HYDROPOWER RESOURCES OF UNDERUTILIZED WATER DAM

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ABSTRACT

The power sector in Nigeria faces significant challenges, with limited electricity access being a primary concern for stakeholders. Almost half of Nigeria's population has no access to electricity supply, notwithstanding the number of untapped energy sources in the country. However, integrating mini or micro hydropower plants into existing and underutilized water dams could help mitigate these challenges. This study evaluates the hydropower potential of the underutilized Eruwa (Opeki) dam to a 1MW mini hydropower plant. The Eruwa (Opeki) dam is a part of the Eruwa water scheme located at Eruwa a town in Oyo State, South West Nigeria. The methods adopted for the research are physical site inspection, data collection, engineering designs, and hydropower simulation. A 706.32kW theoretical power was achieved from the design with an annual energy generation of 4292.89MWh and projected investment and operation/maintenance cost ₦441,000,000 and ₦13,230,000/annum respectively. Annual revenue projection is ₦283,502,455.60, using the present electricity tariff of ₦66.04/kWh. The integration of mini hydropower plants into existing water schemes could increase electricity generation from renewable sources, reduce carbon footprint, and increase revenue for the scheme to prevent underfunding and facilities degradation.

KEYWORDS: Hydroelectric power, Renewable energy, Power generation capacity, Energy access, Energy economics, Dam infrastructure.

5 INTRODUCTION

Hydropower is a renewable energy source that generates power by using dams or diversion structures to alter the natural flow of a river or other body of water. It relies on the endless, constantly recharging system of the water cycle driven by the sun to produce electricity (U.S Office of Energy Efficiency and Renewable Energy, 2021). It is an environmentally friendly source of energy that has the potential to play a significant role in meeting the world's increasing demand for electricity. A hydropower plant is fueled by water, clean energy with lesser pollution in contrast to fossil fuels power plants. It is the most significant renewable energy for electricity generation, with a global installed capacity of 1307GW (Kumar, 2021). In addition, it is expected to remain the largest source of renewable electricity generation (IEA, 2021).

Nigeria, like many other developing countries, is facing an energy crisis with over 50% of its population lacking access to electricity. According to the International Energy Agency (IEA) (2020), Nigeria's energy poverty rate remains high, with an average electricity consumption of 146.84 kWh/capita, which is significantly lower than the global average of 3,074.04 kWh/capita. This is due in part to the poor exploration and exploitation of untapped hydropower potential and other renewable energy sources in the country.

This energy deficit has negatively impacted economic growth, social welfare, and sustainable development in the country. Despite its vast potential for hydropower generation, Nigeria's hydropower capacity remains vastly underutilized (Adewuyi, 2020; Emodi and Boo, 2015, Abban and Awopone, 2021). Nigeria's exploitable hydropower potential is estimated to be 14,120 MW, amounting to more than 50,800 GWh of electricity annually, however, less than 19% was tapped for electricity generation (IHA, 2018).

Furthermore, with over 734.2 MW of electricity generation potential from small hydropower, only 30 MW was produced, which is less than 5% of the potential (Odunfa et.al.,2019). Harnessing all the untapped energy sources through a decentralized grid system with multiple small and mini hydropower plant system could help mitigate energy poverty, increase the economic development of the country, and aids global energy transition plans. Given the increasing demand for electricity in Nigeria and the potential of hydropower as a clean and sustainable source of energy, there is a need to explore the feasibility of harnessing the hydropower potential of underutilized water reservoirs

The objective of this study is to evaluate the technical, economic, and environmental feasibility of harnessing the hydropower potential of the Eruwa (Opeki) Water Dam. The study will assess the potential for hydropower generation at the dam, taking into account factors such as water flow rate, turbine capacity, and power generation

capacity. The study will also evaluate the economic viability of hydropower generation from the Eruwa (Opeki) Water Dam, including the cost of infrastructure development, operations and maintenance, and revenue potential.

The Study area for this research is Eruwa (Opeki) dam, it was constructed in 1967 across the Opeki River sited in Eruwa, a town in Ibarapa East Local Government of Oyo State, Nigeria. The town falls on the 7.53° latitude and 3.42° longitude with an average topography of 149m. The dam has a height of 9.15m and a reservoir capacity of 2 million m³, covering approximately 92 hectares (Ogedengbe and Oke, 2004). It was built to function as a water supply source for the whole Ibarapa community causing the inclusion of a treatment plant capacity of 2.7 million liters/day. Opeki catchment falls within the humid tropical climate with wet seasons (March to November) and dry seasons (December to February) (Idowu and Matins, 2007). It is important to note that the dam and the water treatment facility are presently at 0% utilization. This is due to the degradation of the facility, and damaged distribution network resulting from road construction, all balls down to inadequate funding and maintenance of the scheme.

2. THEORETICAL ANALYSIS

2.1 Engineering calculation for hydroelectric power designs.

2.1.1 Flow rate

Since the maximum storage capacity head = 8.80m,

Dead storage head = 3.16m,

then gross head (H_g) = 8.80 - 3.16 = 5.64m

Due to low head, Kaplan turbine is selected.

Using the general hydropower formula in equation (1) below;

$$P = \eta \times \rho \times g \times H_g \times Q \quad (1)$$

Where, P is Power output (watts) = 10⁶, g is Acceleration due to gravity (m/s²) = 9.81, H_g is Pressure head (m) = 5.64, ρ is Water density (kg/m³) = 1000, η is Turbine efficiency = 90% and Q the Water flowrate (m³/s) is unknown. The water flow rate can be determined using equation (2) as stated below.

$$\text{water flowrate } Q \left(\frac{m^3}{s} \right) = \frac{P}{\eta \rho g H_g} \quad (2)$$

Applying equation (2), The water flow rate is;

$$Q = \frac{10^6}{0.9 \times 1000 \times 9.81 \times 5.64} = 20.08 \text{ m}^3/\text{s}.$$

2.1.2 Penstock

Using Bernoulli's as stated in equation (3) below;

$$p_1 + \frac{1}{2} \rho u_1^2 + \rho g z_1 = p_2 + \frac{1}{2} \rho u_2^2 + \rho g z_2 \quad (3)$$

where ρ is water density, g is Acceleration due to gravity, p_1 is Pressure at penstock inlet, u_1 is Velocity at the dam, z_1 is Height at elevation 1(Head), p_2 is Pressure at turbine outlet, u_2 is Velocity in the turbine and z_2 is Height at elevation 2(Tail). At the same atmospheric pressure of p_1 and p_2 , $z_2 = 0$ since elevation at the dam $z_1 = 5.64$, at the tail race is 0, and flow velocity in the dam is 0. Then the height at elevation 1(Head) is stated in equation (4), the flow velocity u was determined using equation (5), and the water flow rate (Q) is in equation (6);

$$z_1 = \frac{u^2}{2g}, \quad (4)$$

$$\text{flow velocity } (u) = \sqrt{z_1 + 2g} \quad (5)$$

Then flow velocity $u = \sqrt{z_1 + 2g} = \sqrt{5.64 \times 2 \times 9.81} = 10.52 \text{ m/s}^2$

$$\text{water flowrate } Q \left(\frac{m^3}{s} \right) = u \times \text{Area } (A) \quad (6)$$

Then Area (A) = $\frac{Q}{u} = \frac{20.08}{10.52} = 1.91 \text{ m}^2$

Since $A = \pi \frac{D^2}{4}$, Penstock diameter (D) = 1.56m.

Using Darcey Weibach equation as stated in equation (7) below; where h_f is Head loss due to friction, f is Friction factor, L is Length of penstock and D = Penstock diameter

$$h_f = f \left(\frac{l}{D} \right) \frac{u^2}{2g} \quad (7)$$

To get f, the Reynold number (re) must be determined using equation (8)

$$Re = \frac{\rho u D}{\nu} \quad (8)$$

ν is water viscosity = 0.001 Pa.s

Then, $Re = \frac{1000 \times 10.54 \times 1.56}{0.001} = 1.64 \times 10^7$, Reynold number (re) of 1.64×10^7 indicates high turbulence.

Moody Diagram was used since Reynolds number is available. Due to high turbulence, polyvinylchloride (PVC) pipe with loss roughness of 0.0025 is selected to reduce head loss due to friction. Equation (9) was used to determine the relative pipe roughness.

$$\text{Relative pipe roughness} = \frac{\text{loss roughness}}{D(\text{mm})} \quad (9)$$

Then, the Relative pipe roughness = $\frac{0.0025}{1560} = 1.6 \times 10^{-6}$

Tracing the moody diagram, friction factor (f) = 0.007

Therefore: head loss due to friction (h_f) as stated in equation (7) can be determined;

$$h_f = 0.007 \left(\frac{l}{1.56} \right) \frac{10.52^2}{2 \times 9.81}$$

@ $l = 100m$, $h_f = 2.53m$
 @ $l = 50m$, $h_f = 1.27m$
 @ $l = 30m$, $h_f = 0.76m$

30m PVC pipe was selected to have an adequate length and low head loss due to friction of 0.76m. The head loss at intake (h_i) is represented in equation (10), the head loss at gate valve h_v is in equation (11), and the net head (H_{net}) is in equation (12).

$$\text{head loss at intake } (h_t) = f \left(\frac{u^2}{2g} \right) \quad (10)$$

Then, the head loss at intake (h_t) = $0.007 \left(\frac{10.52^2}{2 \times 9.81} \right) = 0.039m$.

$$\text{Head loss at gate valve } (h_v) = 0.15 \left(\frac{u^2}{2g} \right) \quad (11)$$

Then, head loss at gate valve (h_v) = $0.15 \left(\frac{10.52^2}{2 \times 9.81} \right) = 0.84m$, taking 0.15 friction of gate valve.

$$\text{Net Head } (H_{Net}) = H - (h_f + h_t + h_v) \quad (12)$$

Then, the Net head (H_{net}) = $5.64 - (0.76 + 0.039 + 0.84) = 4.0m$

To get the thickness of the pipe, Diamond Plastic Corporation, Nebraska USA PVC pipe with the diameter of 60" (1524mm), thickness of 1.6" (40.64mm) and tensile strength of 7,000Psi was selected. The dimension of the pipe is equivalent to the required diameter.

Therefore, pressure wave velocity (C) is derived from Joukowsky equation and is stated in equation (13)

$$\text{Pressure wave velocity } (C) = \sqrt{\frac{10^{-3} K}{1 + \frac{KD}{Et}}} \quad (13)$$

K is the Bulk modulus of water = $2.19 \times 10^9 \text{ Nm}^{-2}$

E is the young modulus of PVC = $3.275 \times 10^9 \text{ Nm}^{-2}$

t is thickness of pipe (mm) = 40.64, while D is pipe diameter (mm) = 1560m

Then, Pressure wave velocity (C) is;

$$C = \sqrt{\frac{10^{-3}K}{1 + \frac{KD}{Et}}} = \sqrt{\frac{10^{-3} \times 2.19 \times 10^9}{1 + \frac{2.19 \times 10^9 \times 1560}{3.275 \times 10^9 \times 40.64}}} = \sqrt{82083.96} = 286.50 \text{ m/s}$$

Equation 14, 15, and 16 was used to determine the surge pressure, critical time, and net power output;

$$\text{Surge pressure} = c \times \rho \times u \quad (14)$$

$$\text{Critical time} = \frac{2L}{c} \quad (15)$$

$$\text{Net Power Output (P)} = \rho \times g \times H_{net} \times Q \quad (16)$$

Then the Surge pressure = $286.5 \times 1000 \times 10.52 = 3.01 \times 10^6 \text{ Pa} = 437.14 \text{ PSI}$;

$$\text{The Critical time} = \frac{2 \times 30}{286.5} = 0.21 \text{ s};$$

And the Net power output (P) after considering accountable losses is given below;

$$P = 0.9 \times 1000 \times 9.81 \times 4.0 \times 20.08 = 709,145.28 \text{ w} = 709.14 \text{ kW}$$

3 METHODS

Physical site inspection was done, and dam data collected. Suitable hydropower equations, fundamental fluid property equations to cater for losses in the penstock system and simulation using Computer Aided Simulator System for Instream flow and Riparia (CASiMiR) was used. Furthermore, the dam head and the discharge rate of Opeki river form the basis of this study. The available average monthly discharge record of the Opeki River covering only nine years (between 1988 and 1996) shown in Table 1 was collected from Ogun Oshun River Basin Development Authority (Idowu and Matins, 2007). The most previous monthly data was used to evaluate and predict the annual energy generation potential of the dam based on the discharge rate of the river. The dam storage capacity of the reservoir is shown in Table 2.

Table 1: Average Monthly Discharge Rate of Opeki River (m³)

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1988	9.21	8.26	10.59	2.50	2.50	15.63	67.77	54.94	53.36	56.42	9.93	9.83
1989	12.32	16.42	12.13	17.88	26.81	23.54	46.22	77.81	87.70	63.58	26.79	9.37
1990	9.83	7.94	8.76	12.24	13.25	14.79	14.66	14.20	19.80	44.42	41.70	16.58
1991	2.50	2.50	2.50	8.19	2.88	3.58	27.63	99.06	35.64	42.40	7.36	3.62
1992	4.36	2.50	3.89	2.50	2.90	13.43	28.31	68.97	20.76	64.91	16.74	6.47
1993	7.06	6.65	3.75	2.93	2.89	4.86	14.65	11.69	25.10	44.14	9.07	44.14
1994	3.36	6.92	6.73	2.50	2.50	2.50	7.94	8.24	6.51	49.04	37.18	3.57
1995	6.25	5.97	7.88	11.50	17.87	34.33	49.89	29.35	31.23	65.90	34.87	15.34
1996	4.28	4.36	2.50	13.39	16.52	29.86	47.47	55.88	56.65	49.43	36.50	15.84

Table 2: Eruwa dam storage capacity

Storage capacity	Volume (m ³)	Height (m)
Maximum Storage	2,000,000	9.15
Minimum Storage	1,780,000	8.8
Dead Storage	120,000	3.16

4 RESULTS AND DISCUSSION

The results were derived based on the dam data, Opeki river flow discharge, and engineering calculations from hydropower and fluid mechanics equations. Results were backed with Computer Aided Simulator System for Instream flow and Riparia (CASiMiR) as the hydropower simulation tool used for the study.

4.1 Penstock design

With the flow velocity of 10.52 m/s, the flow in the penstock results in turbulence flow at a Reynolds number of 1.64×10^7 . To reduce head losses due to friction on the surface of the penstock material, Polyvinylchloride (PVC)

pipe is selected due to its smooth surface in contrast to steel or concrete. Table 3 below shows the penstock data selected.

Table 3: The Penstock data selected

S/N	Description	Dimension
1	Gross head	5.64m
2	Flow-rate	20.08 m/s
3	Flow velocity	10.52 m/s
4	Penstock diameter	1.56 m
5	Penstock length	30 m
6	Penstock thickness	0.04 mm
7	Penstock tensile strength	48.26 MPa (7000 Psi)
8	Head loss due to friction	0.76 m
9	Head loss due to intake	0.039 m
10	Head loss due to gate	0.84 m
11	Available net head	4.0 m
12	Pressure wave length	286.50 m/s
13	Surge pressure	3.01 MPa (437.14 Psi)
14	Critical time	0.21 Secs

4.2 Simulation Result

The annual data sheet for the hydropower simulation, and that of the daily power generation and discharge rate trend are shown in the appendices. The average daily and annual energy parameter projected by simulator (CASiMiR) is summarized in Table 4 Below.

Table 4: The average daily and annual energy parameter

S/N	Description	Capacity
1	Maximum Power Capacity	706.32 Kilowatt
2	Average Daily Power	490.06 Kilowatt
3	Average Daily Energy Generation	11,761.25 Kilowatt
4	Annual Energy Production	4292.89 Mega Watt Hour
5	Annual Discharge Volume	466,311,168.00 m ³

4.3 Investment Cost and Financial Return

The average total installation costs for new small hydropower projects commissioned between 2015 and 2021 in Africa is approximately \$3500/KW. The operation and maintenance costs (O&M) varied between 1% and 3% of total installed costs per year. However, installing small hydropower plant on an existing dam built for other purposes yields an investment cost reduction of up to 70% compared with a new project (IRENA, 2022, IEA 2021).

4.4 Investment Cost.

The installation of hydropower is taking place on an existing dam built for other purposes.

Therefore, the investment costs per Kw is taken to be: $Installation\ cost \times (1 - 70\% \text{ cost reduction})$
 $= 3500 \times (1 - 0.7) = \$ 1050$

Investment cost of the project = $1050 \times 1000KW = \$ 1,050,000$

Converting to Naira (₦) at official rate of ₦420/\$1 = $1,050,000 \times 420 = ₦ 441,000,000$

Operation and maintenance (O&M) per annum is 3% of investment cost of the project;

Therefore, Operation and maintenance cost = $0.03 \times 1,050,000 = \$ 31,500 \text{ per annum}$

Converting to Naira (₦) at official rate of ₦420/\$1, O&M cost = $\$ 31,500 \times 420 = ₦ 13,230,000$.

4.5 Financial Return.

The financial return is based on the total annual energy generation projected in the simulation, valued to be 4292.89MWh. According to Ibadan Electricity Distribution Company (IBEDC); the distribution company covering the project site, recent price per unit of energy for band B customer is ₦ 66.04/kWh.

Annual revenue from project per annum was derived from the total annual energy generated as calculated below:

Annual revenue = $Total\ annual\ energy\ generated\ (KWH) \times Price\ per\ unit$

$$= 4292.89 \times 1000 \times 66.04 = \text{₦ } 283,502,455.60.$$

5. CONCLUSIONS

This study has evaluated the feasibility of harnessing the hydropower potential of the underutilized Eruwa (Opeki) Water Dam in Oyo State, Nigeria. The results indicate that the dam has significant untapped potential for hydropower generation, which could help to address Nigeria's energy deficit and contribute to sustainable development. The study found that the technical and economic feasibility of hydropower generation from the dam is high, with the possibility of converting it to a 0.71Mw mini hydropower plant with a projected annual energy generation of 4292.89MWh.

Given the potential benefits of hydropower generation from the Eruwa (Opeki) Water Dam and other underutilized water reservoirs in Nigeria, it is recommended that the government and private sector stakeholders invest in further exploration and development of hydropower resources. This could involve the deployment of new technologies and innovations that enhance the efficiency and sustainability of hydropower generation, as well as the implementation of policy and regulatory frameworks that incentivize private sector investment in the sector. Overall, the development of hydropower resources in Nigeria has the potential to create new economic opportunities, improve energy security, and contribute to the country's transition to a low-carbon, sustainable energy future.

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Appendices

Annual parameters

Table About

Annual energy production	4292.89 MWh	Financial return (13.56 Cent/kWh) 582116.47 Euro	
	Mean parameters	Maximum	Minimum
Power	490.06 kW	706.32 kW	0.00 kW
Efficiency	90.00 %	90.00 %	90.00 %
Main discharge	14.79 m ³ /s	20.00 m ³ /s	2.50 m ³ /s
Usable discharge	14.79 m ³ /s	20.00 m ³ /s	2.50 m ³ /s
Head	4.00 m	4.00 m	4.00 m
Daily energy	11761.35 kWh	16951.68 kWh	0.00 kWh
Turbine flow	13.88 m ³ /s	20.00 m ³ /s	0.00 m ³ /s
Discharge weir	0.91 m ³ /s	4.36 m ³ /s	0.00 m ³ /s
Volume of discharge			
Annual discharge	466311168.00 m ³		
Usable discharge	466311168.00 m ³	Discharge weir	28707264.00 m ³
Turbines	437603904.00 m ³		
Energy utilization ratio	84.46 %		
Settings			
Discharge	Q time series	File C:\Users\Akinwale Akintaro\	
Minimum flow regulation	Q time series	File C:\Users\Akinwale Akintaro\	
Head	Constant	4.00 m	
Efficiency	Constant	90.00 %	
Turbine Q min	5.00 m ³ /s		
Turbine Q max	20.00 m ³ /s	File C:\Users\Akinwale Akintaro\	
High water switch point	20.00 m ³ /s		

Annual parameters | Daily parameters | Daily parameters

