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DESIGN AND PERFORMANCE ANALYSIS OF A MODEL PICO SIZE PELTON WHEEL TURBINE

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ABSTRACT

A hydropower generation is an ancient but evergreen energy source that utilises mechanical energy of water strolling down from an elevated head to drive an electric generator thus producing electricity. Small Hydropower (SMH) turbines are rotated by a relatively low-pressure head and usually generates low energy output usually referred to as mini, micro or Pico energy range. Pelton Turbines are generally found to be amongst the most suitable for a low flow power generation. This study focuses on the design of a model Pico size Pelton Wheel modified to use the velocity of water harvested from rooftops during rainfall for the purpose of supplementing energy supply. By the design, the rainwater from the building rooflines are collected and passed through the downspouts into an elevated tank and then the height of the bottom of the tank gives the required head (pressure) to spin the microturbine and then generates a Pico level energy. The Pico size hydropower system directly connected to a small, variable speed, an electric generator which is capable of supplying the power needed for some minimal but very essential functions like charging handsets, mini gadgets and low energy lighting purposes. Specific design calculations, as well as analysis of the model Pico size energy system, was performed to ascertain the feasibility of the design meeting some specified energy needs, thus reducing energy poverty.

Keywords: Design, Rainwater harvest, Micro Grid, Pico Turbine, Hydropower

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1. INTRODUCTION

1.1 General

One of the UNDP Sustainable Development Goals is to ensure the availability of clean energy from sources that are affordable, accessible and sustainable [1]. Energy plays important roles in the economic advancement and technological development of any country [2]. It has been undisputedly noted that uninterrupted power supply is an incessant challenge in developing countries [3]. In most developing nations households depends on generating set mostly to get the energy needed for some minimal but essential purposes like charging gadgets and room lighting. The generating sets make use of fossil fuels which on the long run increase the greenhouse gas emissions thereby contributing to the danger of ozone layer depletion [4]. However, rapid growth in the energy demand above production levels has been linked to the underutilisation of some off-grid renewable energy generation possibilities [5].

Hydropower is a non-polluting process that utilizes high head of flowing water to generate electricity [3]. The turbines are the machines that produce Hydropower. The power of moving water rotates specially designed blades known as vanes or buckets which resultantly drives a connected shaft that goes into a centrifugal type generator [6]. There exist diverse turbine types which can be selected for power generation based on the magnitude of the available head and some other conditions attached to the water [7]. The hydroelectric power plants are classified in various ways like the total head of water available in the reservoir, water storage capacity in a dam, the power generated, total head of water in the reservoir, the nature of electrical load on the power plant [8]. One of the most popular classifications of power plants is according to the amount of power generated and there exist different versions according to different standard organisations and authors [9]. A typical classification is as given below:

- Large Hydropower plants: These are plants that can be generated above 30MW of power
- Medium Hydropower plants: These are plants that can be generated between 1MW and 30MW of power.
- Small Hydro Power plants: these class can be further broken into:
    - Mini Hydropower Plants (100 to 1,000KW)
    - Micro Hydropower plants (5 to 100 kW)
    - Pico Hydropower plants (below 5 kW)[10].

1.2. Typical Features of Pelton Wheel Turbines

A Pelton wheel nozzle shown in Fig 1 is a guide component used to control the water stream at the ideal bearings. A spear needle situated inside the nozzle in an axial direction to direct the stream of water through the nozzle. At the point when the spear needle slides forward into the nozzle, reducing the water quantity and in this manner decreasing the water amount going through the stream and vice visa if the spear is being slid in reverse. The control of the spear can be via programmed pneumatic system [12]. The nozzle is channelled into a pressurized pipeline with a tight nozzle toward one side. The water gushes out of the nozzle with pressure in a stream striking the twofold measured buckets joined to a wheel. Pelton wheel runner is a circular disc with a horizontal shaft passing through the centre and on the peripheral of the disc are buckets fixed at an equidistance [13].

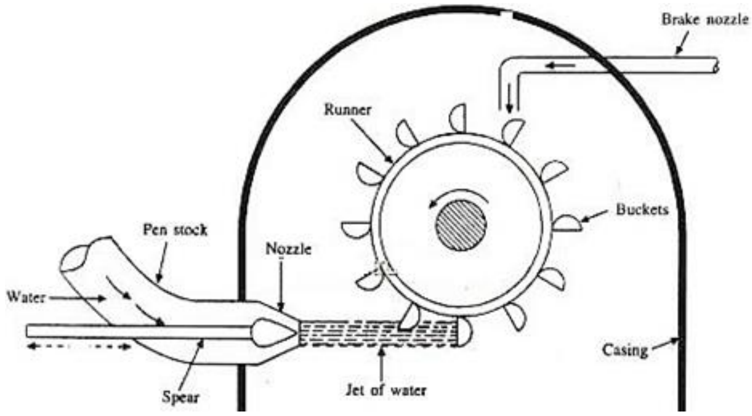

Figure 1 Arrangement of a typical Pelton wheel turbine source: [11]

The bucket is a hemispherical cup with a divider known as a splitter at the middle which tends to split the water jet into two equal parts. The buckets are usually bolted to the runner disc but sometimes they are found a cast as a single unit. The inner surface of the buckets is expected to be as smooth as much as possible to aid the splitting of the jet and thus an efficient drive on the runner. It is advisable to have the buckets bolted to the runner disc for ease of replacement [14]. This is a nozzle arrangement provided such that directs the jet of water on the back of buckets tending to drive the runner in the opposite direction and thus resultantly acting as a brake to either reduce the speed of the runner or bring it to rest in a short time [14]. The Casing can be a metal or Plastic sheet covering gave around the Pelton wheel. The casing is practically to serve as a shield which does not perform any hydraulic capacity. It minimises mechanical losses that may occur through any form of environmental disruptions. The casing can be made of cast or fabricated

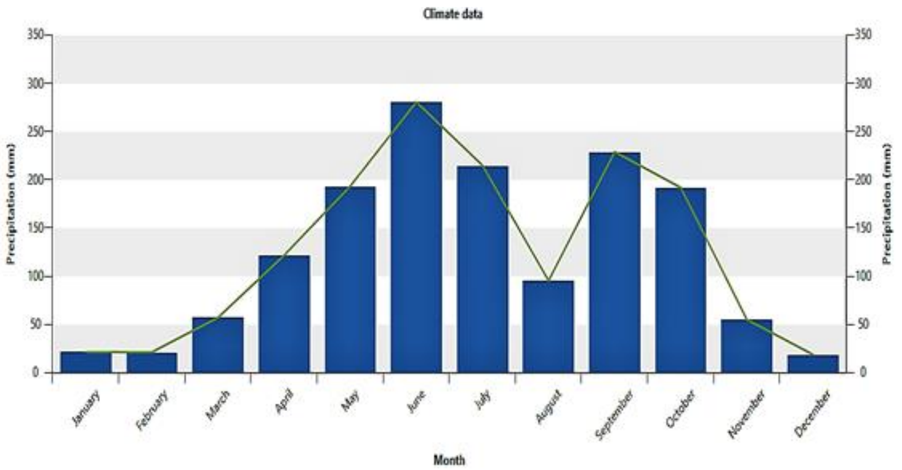

Figure 2 Rainfall Intensity for the study area: Lagos, Nigeria. (Data Source NASA via RetScreen, 2019)

2. THE ARRANGEMENT AND THE WORKING PRINCIPLE OF THE MODEL PICO HYDROPOWER WHEEL TURBINE

The rainwater collected into the overhead tank has potential energy stored in it, which is converted to kinetic energy when it flows through the pipes down the head. This kinetic energy in the water can be harnessed and used for different reasons. The design strives on the procedure that the rainwater from the building rooflines are collected and runs through the downspouts to a raised tank and then the height of the bottom of the tank contribute enough head (pressure) to spin that turbine and thus generates a Pico energy [15]. A preliminary study of the study location shows that there is adequate rainwater for the design around the year. Figure 2 shows an average precipitation data for Lagos, Nigeria as harvested from NASA data [16]. The design was for a multi floor residential built environment in Lagos, Nigeria. The Pico hydropower system utilizes the rainfall harvested to produce electricity by the means of a miniaturised Pelton turbine directly coupled with a small, variable speed, electric generator protected with an automated regulator [17]. The position of the storage tank is mainly at the uppermost position in the building as depicted in the schematic diagram of the design plan showed in Figure 3. The water being stored contains potential energy due to its height i.e. head. The potential energy is converted into kinetic energy due to gravity and supplied to required places thus the potential energy goes unutilized and can be used to obtain useful work for the generation of energy. This makes effective utilization of potential energy that would otherwise waste [18]. An inverter arrangement is provided in the plan to save the energy continuously until it is needed for a household small energy demand [19]

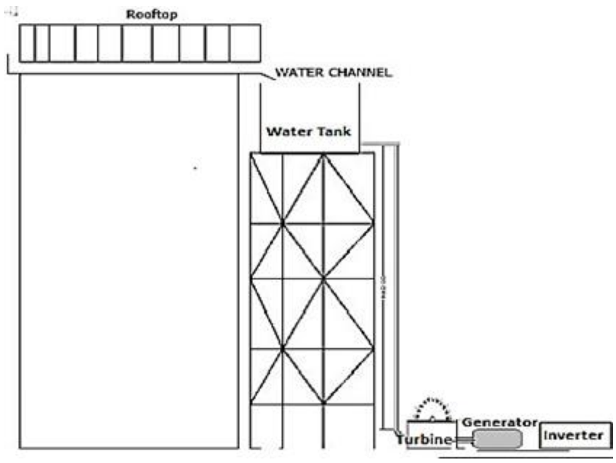

Figure 3 Schematic diagram the Pico Hydropower System

3. THE MODEL PICO HYDROPOWER SYSTEM

Water is harvested from rooftops during rainfall and channelled into a tank on a stand at the side of the story building [20]. The tank discharges water through a pipe to the nozzle which then narrows the flow of water to the Pelton turbine [21]. As the water jet from the nozzle hits the Pelton turbine, it produces power to the shaft connected to the electric generator which then produces electrical power [22]. This system can be coupled with a power storage device which accumulates the small power the system produces. This Pico hydropower would be best used for very light domestic purposes. Figure 3 is a schematic diagram of how the Pico hydropower system's arrangement

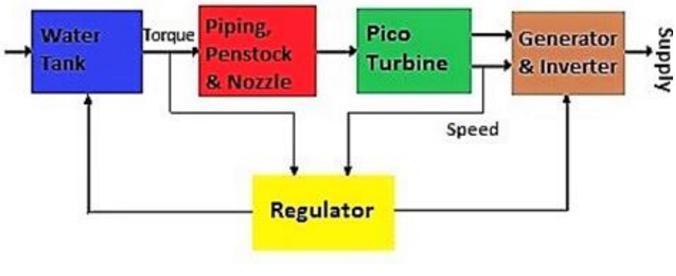

Figure 4 Block diagram the Pico Hydropower System [16]

3.1. Design Specification of the model Pelton Wheel Turbine Components

The water falls from a head (H) at a flow rate (Q). The Pelton wheel is expected to run at a certain specific speed (Ns) to transfer torque (T) to the electric generator to produce power (P) [23]. The expected output produced by the system is Power = 1000W. The distance from the base of the collecting tank to the jet nozzle is considered to be a Head of 10m. Performance depends on hydraulic pressure and flow. The head is the energy per unit weight (or mass unit) of water. The static head is proportional to the height difference of the falls. The dynamic height depends on the speed of the moving water. Each unit of water can do a lot of work, which corresponds to its weight multiplied by the head. The methodology used in this section is as adopted from earlier models of Small Hydro turbine power system [6], [24], [13], [25], [26]

3.1.1. Calculation of Diameter of Pelton Runner

The power available from the waterfall energy can be calculated from the flow and density of the water, the height of fall and the local acceleration due to gravity. In SI units, the performance in terms of Power can be expressed as:

$$P_{ti} = density \times acceleration\ due\ to\ gravity \times C_n^2 \times H \times Q \tag{1}$$

$$Q = \frac{1000}{(1000 \times 10 \times 0.982 \times 10)} = 0.0104 m^3/s$$

Specific Speed, Ns of the turbine

$$N_s = \frac{85.49 \times \sqrt{n_j}}{H^{0.234}} \tag{2}$$

while; nj = number of turbine nozzles = 1

$$N_s = 65.3$$

N = Speed of the turbine

$$= Ns \times H^{5/4} / \sqrt{P_{ti}} \tag{3}$$

$$= 65.3 \times 10^{5/4} / \sqrt{1000}$$

$$= 36.72 rpm$$

$$f(x) = N_s + \sum_{n=1}^{\infty} (n_j) \tag{4}$$

$$N_s = \frac{85.49 \times \sqrt{n_j}}{H^{0.234}} \tag{5}$$

Given; Q = Flow rate of the water from the head = 0.0104m3/s

Dr = Diameter of Pelton Runner = 300mm = 0.3m

And the Diameter of jet Dj = 20mm = 0.02m

3.1.2. Calculation of water jet velocity through the nozzle

The expression for water jet through the nozzle with a velocity Vj in m/s is given as:

$$V_j = C_n \times \sqrt{2} \times g \times H \tag{6}$$

$$= 13.86\ m/s$$

3.2. Calculating the bucket dimensions

The expression for calculating bucket axial width is given as

$$B_w = 3.4 \times D_j \tag{7}$$

$$= 0.068m$$

The expression for calculating bucket radial length is given as

$$B_1 = 3 \times D_j \tag{8}$$

$$= 0.06m$$

3.2.1. Calculating the Bucket Depth

The expression for bucket depth is given as

$$B_d = 1.2 \times D_j = 0.024m \tag{9}$$

3.2.2. Calculating the Number of Buckets

The expression for the number of buckets is given as:

$$N_b = \frac{D_r}{2D_j} + 15 \qquad = 22.5 \tag{10}$$

Here it is clear that the use of 22 buckets will make the micro hydropower system efficient for the proposed power generation of 1kw

3.3. Calculating the Nozzle dimensions

The expression for water flow rate through the nozzle is given as:

$$Q_n = V_j \times A_j \tag{11}$$

The expression for Nozzle area Aj is given as:

$$A_j = \pi \times D_j^2 \tag{12}$$

$$= 1.257 \times 10^{-3}\ m^2$$

$$Q_n = 13.86 \times 1.257 \times 10^{-3} \tag{13}$$

$$= 0.0174\ m^3/s$$

Given;

D_{pn} = Diameter of penstock = 25mm diameter pipe.

D_j = Diameter of water jet = 20mm = 0.02m

β = Nozzle tapper at angle = 15^0

The expression for calculating Nozzle length, L_n is given as:

$$L_n = \frac{D_{pn} - D_j}{Tan\ \beta} \tag{14}$$

3.3.1. Calculation of bucket's distance between the radius center of mass to the center of the runner

The radius of bucket center of mass to the center of the runner is given as:

$$R_{br} = 0.47 \times D_r \tag{15}$$

$$= 0.141m$$

3.3.2. Calculation of the force on each bucket

$$F_d = \rho w \times Q_n \times V_j^2 \tag{16}$$

$$= 3342.53N$$

The require Force in each bucket is:

$$F_{dr} = F_d \times Safety \text{ factor} \tag{17}$$

$$= 3342.53 \times 3.5$$

$$= 11698.87N$$

3.4. Calculating the Maximum Turbine efficiency

The expression for Calculating input power to the turbine is:

$$P_{ti} = \frac{\rho w \times Q_t \times V_j^2}{2} \tag{18}$$

$$= 998.89W$$

And the Power output generated by the turbine can be calculated as:

$$P_{to} = \rho w \times Q_t \times V_{tr} \times [(V_j - V_{tr})(1 + \Psi \times \cos \Phi)] \tag{19}$$

Runner tangential velocity $V_{tr} = {}^{\pi N D_r}/_{60}$ (20)

$$= 23.56\ m/s$$

Recall, Ψ = roughness coefficient of the Bucket (0.98)

Φ = Angle of Deflection between jet and bucket $180^{\circ} - \theta$

$$\theta = (160^{\circ}\ to\ 170^{\circ})$$

$$\Phi = 180^{\circ} - 160^{\circ} = 20^{\circ}$$

$$\therefore \quad P_{to} = 1000 \times 0.0104 \times 6.3756 \times [(13.86 - 6.3756)(1 + 0.98 \times \cos 20^{\circ})]$$

$$= 457W$$

3.5. Design of the shaft

The overall Efficiency η is assumed to be 70%, which is within the specification range.

Radial shaft velocity; $\omega = \frac{2\pi N}{60}$ (21)

$$= 157.08\ rad/s$$

Power = Torque x radial shaft velocity (22) i.e $P = T \times \omega$ (23)

$$T = P/\omega$$

$$T = 1000/157.08 = 6.366\,N/m$$

The working shear stress, $\delta = \frac{16Mt}{\pi d^3}$ (24)

Where d = diameter of the shaft,

Allowable working shear stress, $\delta = \frac{Ultimate\ shear\ stress}{Factor\ of\ safety}$ (25)

M_t = T (M_t is the maximum allowable torque) (26)

The specified ultimate shear stress for the mild steel shaft is 220MPa and the selected factor of safety is 15.

$$\delta = \frac{220 \times 10^6}{15} = 14667.67\,N/m^2 \quad (27)$$

$$D^3 = \frac{16Mt}{\pi\delta} = \frac{\sqrt[3]{[16 \times 15]}}{\pi \times 14667.67} \quad (28)$$

$$D = 0.1733m$$

Shaft diameter, $d = 173mm$

Therefore, $d = 200mm$ is used for design purposes

3.6. Design Parameters in Summary

The summary of the Calculated design parameters is as represented in Table 1 below.

Table 1 Parameters of the model Pelton wheel turbine as obtained from design Calculations

S/N	Parameters	Calculated
1	Flow rate, Q	0.01403 m^3/s
2	The velocity of the water jet through the nozzle	13.86m/s
3	The diameter of Pelton runner, D_r	0.3m
4	Bucket axial width	0.068m
5	Bucket radial length	0.06m
6	Bucket depth	0.024m
7	Number of buckets	22
8	The radius: centre of the bucket to the centre of the runner	0.141m
9	Runner tangential velocity	23.56m/s
10	Force on each bucket	11698.87N
11	Bucket roughness coefficient, Ψ	0.98
12	Deflection angle between bucket and jet, Ө	160^0 to 170^0
13	The torque produced by the shaft	6.366N/m

4. ANALYSIS FOR THE PELTON WHEEL

The Pelton wheel system conceptualized and designed were analysed to ascertain the best material to be used among the readily available materials and methods using Autocad Inventor Simulation package. Also, the performance evaluation of the design was carried out using a pilot scale experimental arrangement to evaluate the expected efficiency curve while using the

Pico scale hydropower generation scheme. And lastly, the authors carried out the greenhouse emission analysis using Retscreen; an international standard energy simulation and analysis package.

4.1. Material Selection

The cost of producing the components of a Pico SHP is a major factor of consideration. There is particular attention on keeping the cost of materials for the fabrication of the Pelton wheel very low [27]. Various sizes of PVC pipes, couplings and plastic/metal sheet for case building are all less expensive and locally available materials. Some market available Micro/Pico wheel are made of CA6NM – a case hardened combination of iron, chromium, nickel, and molybdenum while some were made of nylon resin embedded with fibreglass, Stainless Steel, Cast Iron and mild steel [28]. This low-cost Pico Pelton wheel has been modelled to use material made of Aluminium Alloy; easy to cast, less corrosive and has been modelled using Autodesk Inventor to verify the material as suitable for the tensile fatigue and impact of the working conditions [11]. Figure 5 shows the simulated material's structural displacement under an applied force during the analysis. Table 2 below shows the physical properties value of the simulated working material for the Pelton wheel.

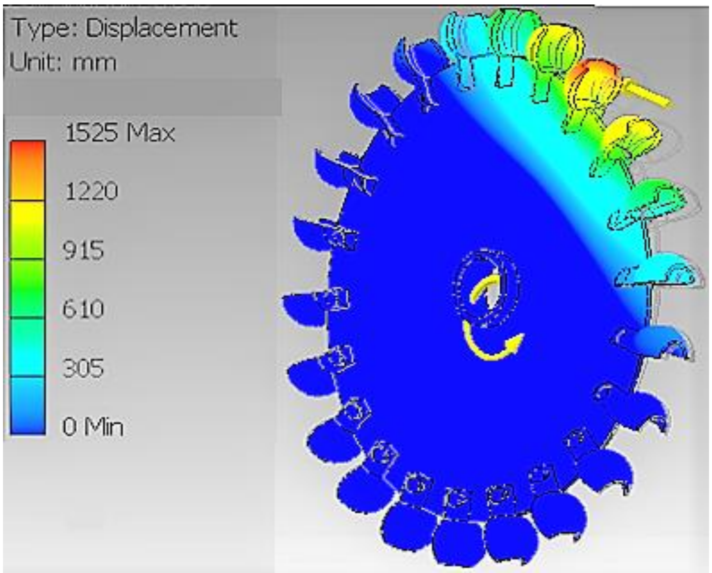

Figure 5 Pelton wheel Showing the displacement as a result of the acting forces

Table 2 Properties of the Pelton turbine made of Aluminium Alloy.

Properties	Value
Mass Density	2700kg/m3
Yield Strength	275.00 MPa
Ultimate Tensile Strength	310.00 MPa
Young Modulus Stress	68.9 GPa
Shear Modulus Stress	25.90 GPa
Maximum Von Mises Stress	1646.82 MPa
Maximum 1st Principal Stress	1575.47 MPa
Maximum 3rd Principal Stress	192.16 MPa
Displacement	23.0714mm

4.2. Performance Analysis

The Pico-scale power system's performance was investigated using excel spreadsheet where all the mathematical expressions were programmed and the efficiency was varying to obtain the efficiency curve of the designed Pelton wheel assuming linearity and neglecting external forces that may be exerted on the system during operation. Figure 6 shows the characteristic of the designed Pico Pelton Turbine. The operating efficiency is expected to be within the range of 50% and 80% while the Pico hydro generator is expected to produce between 300W and 1000W with the generator running at about 70 r.p.m by estimation. Figure 7 shows an estimation of reduction in the greenhouse emission as a result of using the designed rainwater Pico-Hydro system was carried out using Retscreen Analysis software which shows a possibility of having 17% reduction in kgCO_2 [29].

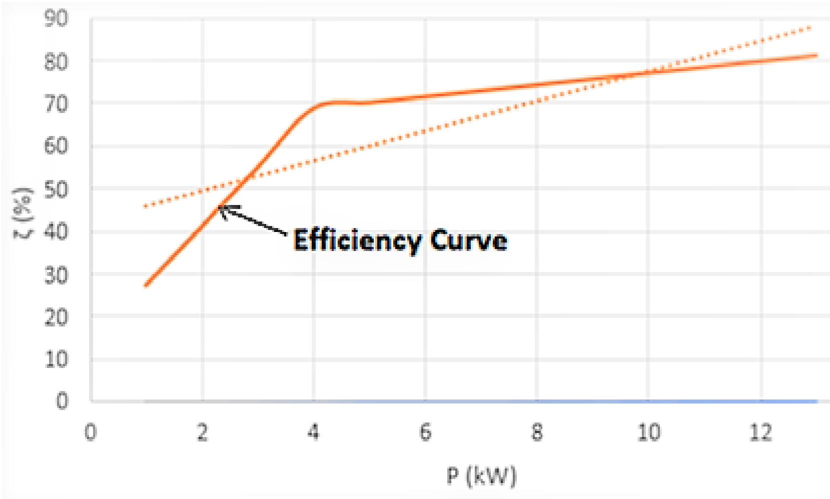

Figure 6 Performance Characteristic of the designed Pico Pelton Turbine

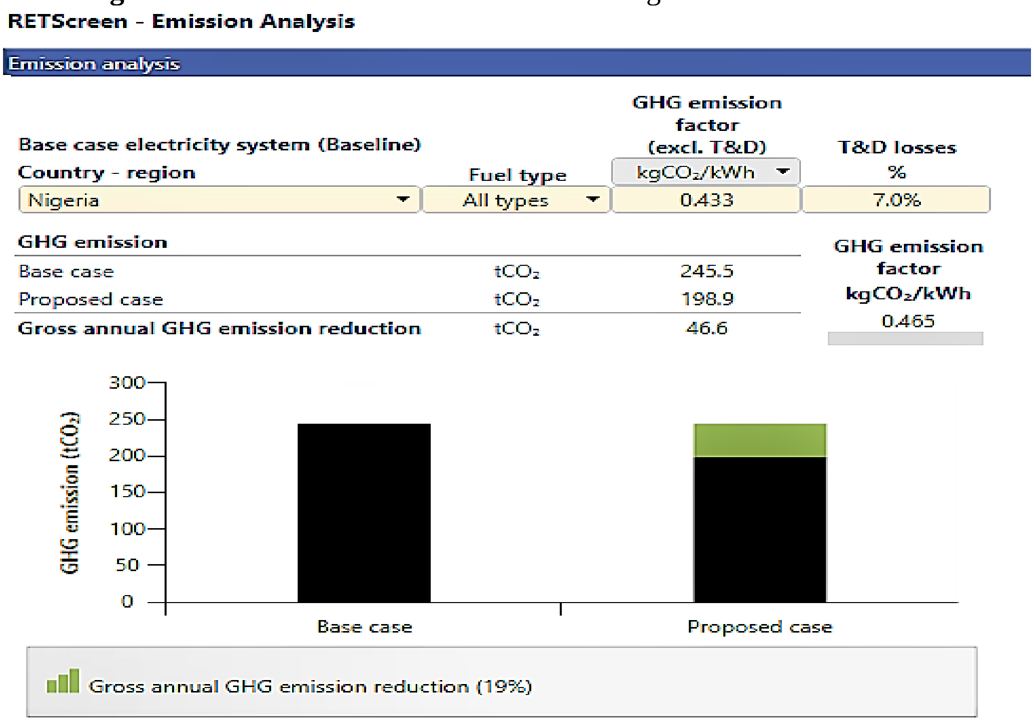

Figure 7 Estimated reduction in greenhouse Emission for the designed System.

5. CONCLUSION

In developing countries, where the power supply is not stable, Microgrids has been seen as a viable alternative to complement the shortages. Sometimes, the power required for certain functions like charging handsets, mini gadgets and low energy lighting purposes, is so minimal but very essential. These needs can be met by having the Pico-scale power generated, stored and used when needed rather than using fossil fuel generating plants which contribute to greenhouse emissions. This project presented the design and analysis of a Pelton wheel turbine model for a Pico-sized hydropower system powered by rainwater collected on rooftops. The parameters of the model Pelton wheel turbine were as summarised in Table 1. However, the energy supply may actually depend on factors such as the availability of rain for an adequate supply of water, its height and storage capacity. The energy produced by the Pico hydropower system will be used as a supplement to reduce the total dependence on the national grid. The proposed system can also be used as a component of multi-directional microgrid hybrid energy system to enhancement power quality capabilities [7].

An estimation of reduction in the greenhouse emission as a result of using the designed rainwater Pico-Hydro system was carried out using Retscreen Analysis software which shows the possibility of having 17% reduction in kgCO2. On a larger scale, this pilot scale design can be scaled up to become an appropriate alternative to solving the energy crisis as a result of global growing energy. Anilkumar, Simon, & Prasad, (2017) has shown a possibility of constructing an underground reservoir that will serve as a collection tank for the water from the turbine and then connecting a low energy pump to make a feedback system by returning the used water back into the overhead tank, thus a longer running period and increasing both the effectiveness and efficiency of the system designed.

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NOMENCLATURES

- β angle of the nozzle
- ζ overall efficiency of the turbine
- Ψ roughness coefficient of the bucket
- Φ deflection angle between buckets
- ω radial velocity of the shaft
- δ working shear stress
- A_j area of the jet nozzle
- B_d bucket depth
- B_l bucket radial length
- B_w bucket axial width
- D diameter of the shaft
- D_j diameter of water jet
- D_{pn} diameter of the penstock
- D_r diameter of Pelton runner
- F_d force on each bucket
- F_{dr} force require in each bucket

H head of water
L_n length of the nozzle
M_t maximum allowable torque
N speed of the turbine
N_b number of buckets
Ns Specific speed of Pelton wheel
P power of the electric generator
P_{ti} power input to the turbine
P_{to} power output by the turbine
Q flow rate of water
Q_n water flow rate through the nozzle
R_{br} radius of bucket center of mass to center of runner
T torque of Pelton wheel
Vj velocity of water through the nozzle
V_{tr} tangential velocity of runner

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