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OPTIMAL SELECTION OF HYDRAULIC TURBINES FOR SMALL HYDRO ELECTRIC POWER GENERATION – A CASE STUDY OF OPEKI RIVER, SOUTH WESTERN NIGERIA

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ABSTRACT
The overall net annual energy production from Small Hydro Power (SHP) scheme using stream flow or run-of-water is usually depend on the water height (head), stream flow (discharge) and turbine efficiency. However, experience has shown that the annual capacity of the plant which is a measure of what the machine can deliver throughout the year without interruption is usually in conflict with theoretical power rated output when analysed with different turbines and subjected to the same values of the above mentioned variables. This work provided a platform for optimum selection of SHP turbine for optimum power output that can be sustained throughout the year. Conventional power Equations, seven years of mean daily flow and a medium range of gross head of Opeki River, Ogun State, Nigeria were used to develop Flow Duration Curve (FDC) and annual energy production of a proposed SHP power plant. A net head of 37m and reserved flow of 2.97 m^3/s was used. Seven hydraulic turbines were examined using their permissible efficiencies. Results from the analysis showed that turbines that gave maximum and minimum power outputs respectively did not imply maximum and minimum annual capacities. The study indicates the usefulness of this work as a guide for SHP scheme.

Keywords: *optimal selection, SHP turbine, flow duration curve, energy efficiency, annual capacity factor*

1. INTRODUCTION

Small hydro power (SHP) has the potential to become an important contributor to global energy; especially, in developing countries like Nigeria [1, 2]. With rural electricity access levels at approximately 28 %, Nigeria faces an acute shortage of rural electricity supply [3]. Most potential small hydro sites in Nigeria are located within the proximity of off - grid, rural communities [4] where potential beneficiaries have limited access to finance [3]. As a consequence, technological challenges alongside the cost associated with assessing potential SHP sites have served as substantial barriers to the widespread development of SHP in Nigeria [5, 6, 7].

SHP schemes usually have facilities with rated output of 10 MW or less [8, 9]. Since the primary objective of SHP generation is to maximize plant energy production at minimal cost; a SHP does not need the large reservoirs generally associated with large scale hydroelectric power generation. Most SHPs are run - of - river projects without significant water storage facilities [9, 10]. As a consequence, turbine efficiency, and; the plant's power output fluctuates with the annual variability of the river flow to be exploited [8]. Since the turbine is the primary energy conversion machinery in a SHP; an evaluation of the hydrodynamic response of alternative hydraulic turbines to the annual variability of stream flow is a prerequisite to appropriate turbine selection. Optimum turbine selection leads to maximization of annual energy production. Failure to do so, often leads to a significant deficit in annual energy production and low annual plant capacity [8, 9]. Turbine selection depends mainly upon the site characteristics; principally, available head and the flow regime of the river to be exploited [10, 11]. The aforementioned characteristics also determine the energy available at the study area. The extensive nature of these evaluations necessitated the development of an algorithm in Visual Basic programming language to implement the design.

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2. EQUATIONS AND FORMULAE

Various mathematics and expression describing procedural steps in choosing appropriate SHP components are presented below.

2.1 Annual Flow Duration Curve (FDC)

A reliable assessment of available energy at a potential small hydro site begins with an understanding of the annual flow characteristics of the river. Rivers annual flow characteristics are depicted by the FDC. It summarizes the hydrological characteristics of river flow [12]. FDC is a curve with probability of exceedance (%) on the x - axis and the flow rate (m^3/s) on the y - axis, which provides information on the probability of a specific flow being equalled or exceeded [12, 13]. Development of FDC from mean daily flow records can be achieved by using statistical applications.

In order to avoid sections of the watercourse being depleted, with adverse environmental impacts downstream, a minimum non-usable flow is usually prescribed by environmental regulations to bypass the SHP [8, 9]. This minimum flow, also termed the reserved flow (Q_r), must remain unused when abstracting water from a river to drive the turbine. Given Q_i represent flow values constituting the FDC for the river to be exploited. The actual flows available to the turbine for power generation, termed Q_j, is estimated using Equation (1) [8, 9];

$$Q_j = Q_i - Q_r \tag{1}$$

Where, i, j = {0, 1, 2, 3, ..., n}, i, j are subscripts indicating the exceedance probability of each flow on the FDC, n is the number of equally spaced intervals on the FDC, Q_i is the flows constituting the primary FDC (m^3/s),

Q_j is the flows constituting the secondary FDC (m^3/s), Q_r is the reserved flow (m^3/s).

2.2 Head (H)

The gross head is the vertical distance between upper to lower surface water levels [8, 11]. Estimation of gross head can be made from large topographical maps or by field measurements using leveling or total station. Both methods were used to estimate gross head in this study. After measuring the gross head, allowances must be made for the losses associated with the water conveyance structures and tail water effect. Therefore, the actual head available for power generation, termed the net head (H_n), was estimated using Equation (2) [8,10]:

$$H_n = H_g - [\zeta_h(H_g) + h_w] \tag{2}$$

Where, H_n is the net head (m), H_g is the gross head (m), ζ_h is the maximum hydraulic losses (typically 3 – 8%), h_w is the maximum tail water level (m).

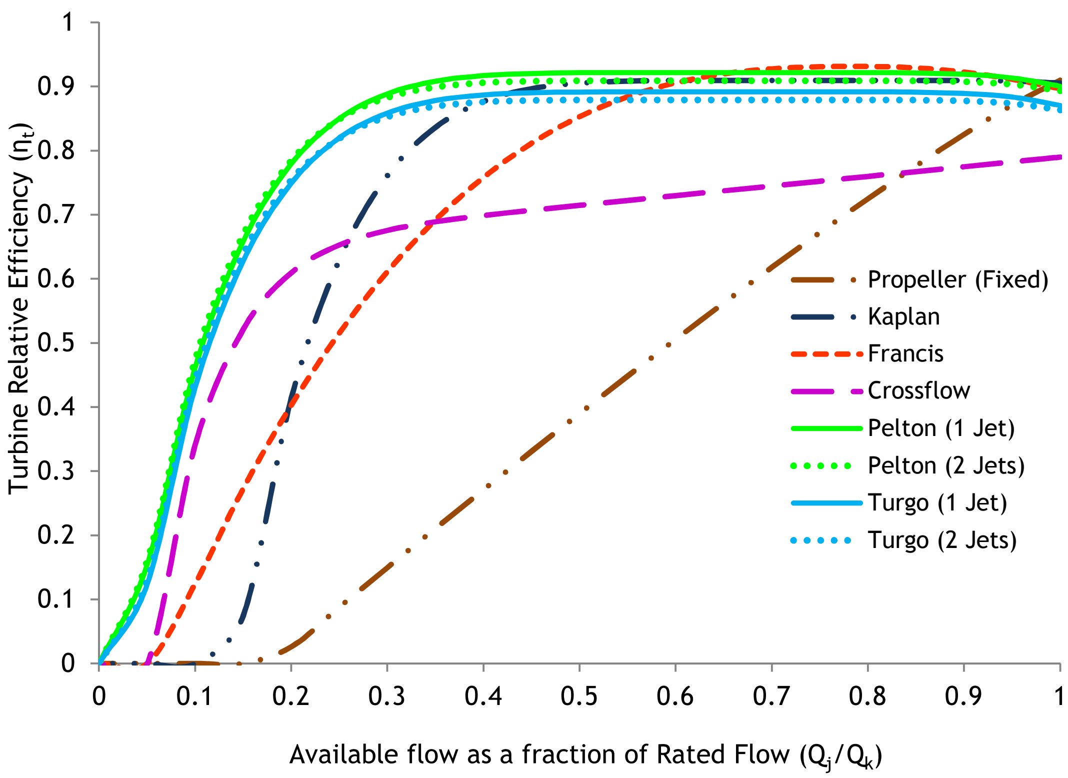

Figure 1. Turbine Efficiency Curves

2.3 Turbine relative efficiency

A hydraulic turbine's relative efficiency describes a turbine's efficiency at design flow and reduced flows as depicted by a turbine efficiency curve (TEC). The relative efficiency of a specific turbine was determined by the energy conversion technology employed by turbine [8, 9]. Studies carried out on Kaplan, Propeller, Francis, Crossflow, Pelton and Turgo turbines have established formulae to determine their relative efficiencies under varying conditions of head and flow. The details of the formulae are described in details in [10], the procedures were adopted to develop the turbine efficiency curves used in this study as presented in Figure 1.

2.4 Power output of a SHP

Considering the overall efficiency of components in the SHP; the power output of the plant was estimated using Equation (3) [11]:

$$P = \rho g Q H_n \eta_o \quad (3)$$

where, ρ is the water specific density (1000 kg/m^3), g is the acceleration due to gravity (9.8 m/s^2), Q is the stream flow (m^3/s), H_n is the net head (m) and η_o is the overall efficiency of the system (%).

2.5 Power duration curve (PDC)

The PDC depicts the power output of the SHP in response to the annual variability of streamflow. Modification of the Equation 3 to consider the distinct efficiencies and losses of various components at the SHP and taking Q_k as the plant's rated flow, Equation 4 defines the power output of the SHP scheme due to the available flow (Q_j), relative to the plant's rated flow (Q_k) [10]. Hydraulic head losses (H_h) were estimated using Equation 5.

$$P_{k(j)} = \rho g Q_j [H_g - (H_h + H_w)] \eta_{t\,k(j)} \eta_g (1 - \zeta_t)(1 - \zeta_t) \quad (4)$$

In (4) j, k = {0, 1, 2, 3, ..., n}, n is the number of equally spaced intervals on the FDC, Q_j is the min (Q_j, Q_k), "j" and "k" indicate the exceedance probability of a flow value on the FDC, η_t is the turbine relative efficiency (obtained from Figure 1), η_g is the generator efficiency (typically 93 – 97%), ζ_t is the transformer losses (typically 1 – 3%), ζ_p is the parasitic electricity losses (typically 1 – 4%), ρ is the density of water (1,000 kg/m^3), g is the acceleration of gravity (9.81 m/s^2), Q_j is the available flows (m^3/s), Q_k is the plant's rated flow (m^3/s), H_g is the gross head (m) and H_h is the hydraulic head losses (adjusted over the range of available flows) .

$$H_h = H_g \zeta_h \{Q_j^2 / Q_k^2\} \quad (5)$$

where ζ_h is the maximum hydraulic losses (typically 3 – 7%). Equation 6 presents the tail water losses over the range of available flow.

$$H_w = h_w \left\{ (Q_j - Q_k)^2 / (Q_{max} - Q_k)^2 \right\} \quad (6)$$

Where H_w is the tail water head losses (adjusted over the range of available flows) and are defined for only ($Q_j > Q_k$); h_w is the maximum tail water level (m) and Q_{max} is the maximum river flow obtained from the primary FDC (m^3/s).

The plant's rated output (P_k) was obtained from the Equation 4 when $Q_k = Q_j$ and the power outputs from the Equation was used to establish power duration curve (PDC) for the proposed plant using alternative turbines.

The plant's rated output (P_k) when rated flow equals the minimum annual flow (i.e. $Q_k = Q_{min}$) defines the minimum power potential (P_{min}) of the plant [14].

The plant's rated output (P_k) when rated flow equals the mean annual flow (i.e. $Q_k = Q_{mean}$) defines the average power potential (P_{mean}) of the plant [14].

2.6 Annual energy production (E)

An approximation of the area of the region under the power duration curve provides an estimate of the SHP's annual energy projection. The area was approximated by mathematical expression presented in (7).

$$\int_a^b f(x)dx = \frac{h}{2} \sum_{z=0}^{n} \{f(x_z) + f(x_{z+1})\} \quad (7)$$

The trapezoidal rule was modified to accommodate the plant's availability as presented in (8) [15]:

$$E = \frac{h}{2} \sum_{j=0}^{n} \{P_{k(j)} + P_{k(j+1)}\} t_y \quad (8)$$

In (8), E is the the annual energy produced by the SHP (kWh), $P_{k(j)}$ is the power outputs from (4), A =plant's annual availability (typically 85 – 98%), t_y is the approximated number of hours in a year (8760 hrs), h is the percentage spacing of intervals on the PDC (1%).

2.7 Annual capacity factor(C)

SHP annual capacity factor is the ratio of the plant's estimated energy production to the plant's potential energy production if it had operated at rated output for the whole year [8]. A higher capacity factor plant is more dependable. Annual capacity was estimated using Equation 9 [8, 10];

$$C = E / (P_k t_y) \quad (9)$$

Where C is the plant capacity factor

2.8 Turbine application range chart

Given specific site characteristics of head and flow, turbine application range charts have been developed to assist with the selection of appropriate turbine(s). These charts are shown in Figures 2 and 3. A combination of net head and rated flow fall within the operational envelope of an appropriate turbine. Envelopes of alternative turbines may overlap and slight variations exist among charts produced by different manufacturers.

3. ANALYSIS AND DISCUSSION

Seven years mean daily flow (m^3/s) and head (m) were collected from Opeki river, Ogun State, Nigeria. The study area is located at Abidogun Village, Iseyin Local Government Area, Oyo State, Nigeria. It is under the jurisdiction of Authority: Ogun-Osun River Basin Development Authority (OORDBA).

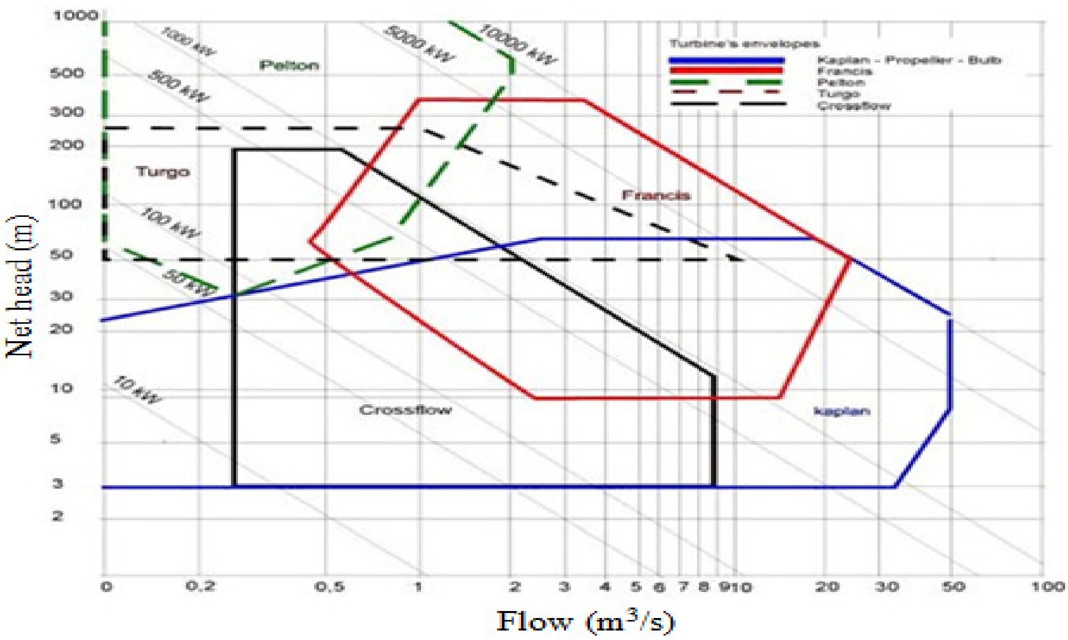

Figure 2: Turbine application range chart [16]

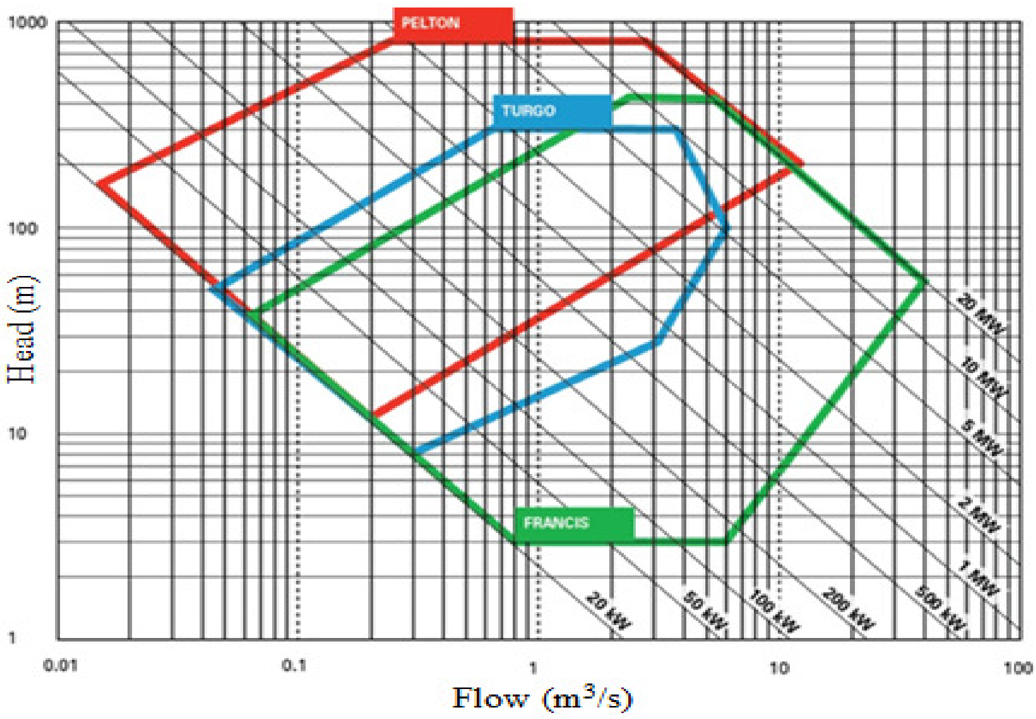

Figure 3: Turbine types and range of applications [17]

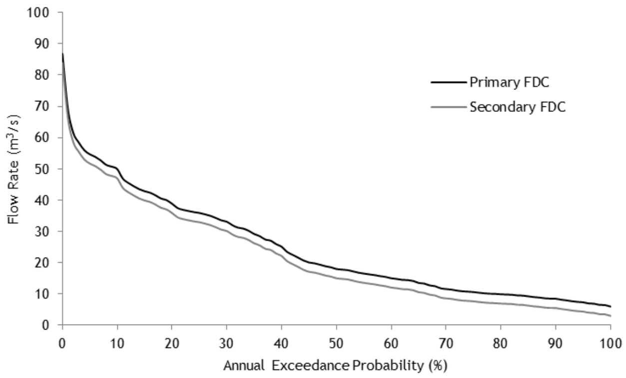

Figure 4: Primary and Secondary Flow Duration Curves for Opeki River

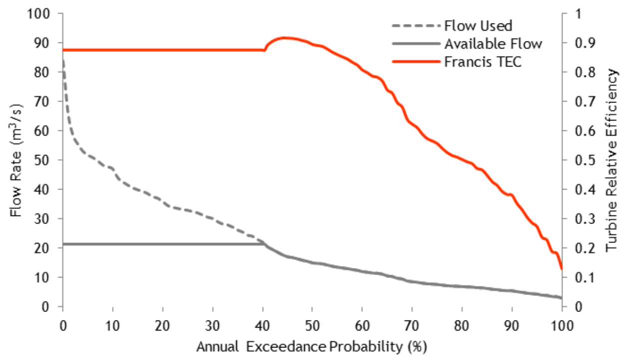

Figure 5: TEC for a single Francis turbine at P_{mean}

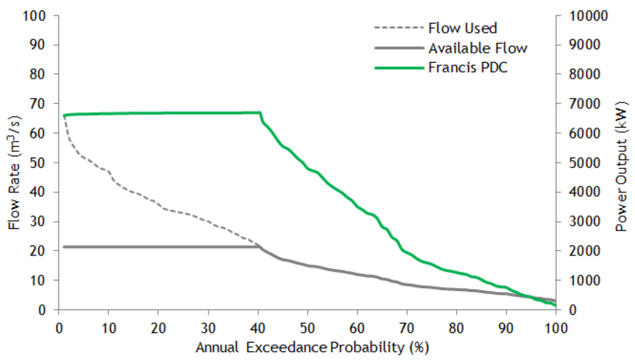

Figure 6: PDC for a single Francis turbine

The initial estimated site conditions are: gross head (H_g) is 40.0 m, maximum tailwater level (h_w) is 1.0 m and reserved flow (Q_r) is 2.97 m^3/s. The estimated net head from the Equation 2 is 37.0 m. The anticipated system efficiencies and losses are: generator efficiency (η_g) is 98 %, transformer losses (ζ_t) is 1%, conduit head percentage losses ζ_h) is 5 %, parasitic electricity losses (ζ_p) is 1 % and plant availability (A) is 98%.

A reserved flow (Q_r) equal to 50% of the annual minimum flow (2.97 m^3/s) was sustained as per environmental regulations using (1). Primary and secondary flow duration curves consisting of flows available for power generation were established and presented in Figure 4.

3.1 Power and energy assessment

In order to estimate average power potential (P_{mean}), annual mean flow (Q_{mean}) was taken as rated flow. An estimate of Q_{mean} for the multi - year period represented by the secondary FDC was used to establish Q_{mean} at $Q_{40.5}$ with its value equals 21.4 m^3/s. Since plant rated output was obtained from (4) when $Q_k = Q_j$; (4) was employed together with the appropriate turbine relative efficiencies derived from Figure 1 to compute rated output at P_{mean} for Kaplan, Propeller, Francis, Crossflow, Pelton and Turgo turbines respectively.

By employing (4) along with the appropriate turbine relative efficiencies derived from Figure 1 for available flow on the secondary FDC, the variation in turbine efficiency and consequent change in plant output as annual stream flow deviates from rated flow was computed for alternative turbines. Since a turbine will only accept flows equal to or less than its rated flow when available flow exceeds the turbine's rated flow, the excess flow bypasses the turbine and the rated flow constitute the flow used for computation.

From this exercise turbine efficiency curves (TEC) and power duration curves (PDC) were plotted respectively. The turbine efficiency curve describes the variation in turbine efficiency as available flows falls below the rated flow of the turbine while the power duration curve depicts the drop in the plant rated output when available flows falls below the turbine's rated flow. Practically, the PDC defines the plant's ability to sustain output at reduced flows especially during the dry season. The exercise was repeated for the seven selected turbines, the samples of which were plotted in Figures 5 and 6. Figure 5 shows turbine efficiency curve for Francis turbine, while Figure 6 shows its PDC.

The annual energy production was projected by approximating the area of the region under the power duration curve for each turbine using Equation 8 and from the plant's annual energy production, annual capacity factor was estimated using Equation 9. The results obtained are presented in Table 1.

Though it is observed from Table 1 that Pelton and Turgo turbines are projected to give reasonably higher annual energy production in MWh.

Table 1: Relationship between Turbines Efficiencies and P_{mean}

Alternative Turbine Types	Efficiency At Rated Flow (%)	Peak Efficiency (%)	Lowest efficiency (%)	Plant Rated Output (Kw)	Annual Capacity Factor (%)	Annual Estimated Energy Production (Mwh)
Kaplan	92.0	92.4	0.0	7033	65.0	40000
Propeller	92.4	92.4	0.0	7067	53.1	32833
Francis	87.5	91.7	12.9	6694	62.1	36388
Crossflow	79.0	79.0	49.2	6042	64.3	34008
1 Jet Pelton	91.4	93.6	63.2	6993	66.9	40958
2 Jets Pelton	90.7	92.3	64.4	6940	66.8	40600
1 Jet Turgo	88.4	90.6	60.1	6763	66.9	39615
2 Jets Turgo	87.7	89.4	61.4	6711	66.8	39260

Table 2: Estimation of annual energy generation from Kaplan Turbine

Suitable Turbine Type	Gross Head (m)	Net Head (m)	Efficiency at Rated Flow (%)	Plant Rated Output (kW)	Annual Energy Production (MWh)	Capacity Factor (%)
Kaplan	10	8.5	90.6	1733	9507	62.7
Kaplan	20	18.0	92.1	3523	19797	64.2
Kaplan	30	27.5	92.1	5285	29934	64.7
Kaplan	40	37.0	92.0	7033	40000	65.0
Kaplan	50	46.5	91.8	8774	50012	65.1
Kaplan	60	56.0	91.6	10510	60000	65.2
Kaplan	70	65.5	91.5	12241	69966	65.3

Table 3: Estimation of annual energy generation from Francis Turbine

Suitable Turbine Type	Gross Head(m)	Net Head(m)	Efficiency at Rated Flow (%)	Plant Rated Output (kW)	Annual Energy Production (MWh)	Capacity Factor (%)
Francis	10	8.5	65.6	1254	4585	41.7
Francis	20	18.0	81.3	3112	15545	57.1
Francis	30	27.5	85.6	4914	26072	60.6
Francis	40	37.0	87.5	6694	36388	62.1
Francis	50	46.5	88.5	8462	46607	62.9
Francis	60	56.0	89.1	10222	56777	63.4
Francis	70	65.5	89.5	11976	66902	63.8

An examination of the turbines' application range charts in Figures 2 and 3 shows that Francis and Kaplan turbines are more practically realizable at P_{mean}. A critical examination of Figure 5 shows that Francis turbine's efficiency is expected to decline annually from 87.5% to 12.9%, at the peak of dry season. Annual energy production is estimated at 36388 MWh as shown in Table 1. Similarly, it can be observed from Figure 5 that, Kaplan turbine's efficiency is expected to decline annually from 92.4% to 0%, at the peak of dry season. Despite its total loss of efficiency at minimum flow, the Kaplan turbine exhibits better part – flow efficiency compared to the Francis turbine. Hence, annual estimated energy production with Kaplan turbine is 40000MWh at 65.0% capacity factor which exceeds values obtained for a single Francis turbine at P_{mean} as shown in Table 1.

It was also observed from Figure 6 that the proposed plant is estimated to a have rated power output of 6.7 MW with a single Francis turbine installed. This is marginally less than the rated power output of 7.0 MW achieved with a single Kaplan turbine. In addition, plant power output is expected to decline annually between 6.7 MW and 142 kW with a single Francis turbine whereas a total loss of generation is anticipated annually with a single Kaplan turbine. The decline in power output annually is mainly due to reduction in streamflow during the dry season as observed from Figure 6.

Based on the available data considered at the study area, further analysis was carried out on Kaplan and Francis turbines to determine the effect of varying heads on turbine efficiency, plant rated power output, annual estimated energy production and capacity factor at P_{mean} for heads between 10m and 70m, considering the aforementioned specified inputs. The results are presented in Tables 2 and 3 respectively.

From Table 2, the Kaplan turbine's efficiency at rated flow remains relatively constant at different heads. Although an increase in net head results in a significant increase in rated power output and estimated energy production, capacity factor at P_{mean} remains relatively constant; varying marginally from 62.7% for a net head of 8.5m to 65.3% for a net head of 65.5m. The implication of the observations in Table 2 is that a Kaplan turbine is well suited for the study area at low, medium heads and P_{mean}. This was validated by the turbine application range chart in Figure 2.

Similarly it is observed in Table 3 that the Francis turbine's efficiency at rated flow; increases significantly from 65.6% for a net head of 8.5m to 81.3% for a net head of 18m, with capacity factor increases significantly from 41.7% for a net head of 8.5m to 57.1% for a net head of 18m. Although an increase in net head results in a significant increase in rated output and estimated energy production. Capacity factor remains relatively constant above a net head of 27.5m, varying marginally from 62.1% at a net head of 37m to 63.8% at a net head of 65.5m. The implication of the observations in Table 3 is that Francis turbine is not well suited for the study area at low heads and P_{mean}. Francis turbines, thus, perform better at P_{mean} for medium heads above 30m as validated by the turbine application charts presented in Figures 1 and 2.

4. CONCLUSION

Nigeria current electricity generation capacity is yet to meet up demand of her populace. Majority of rural and sub- urban dwellers are living far from grid system. Nigeria is blessed with a lot of streams and rivers that can be used to facilitate SHP scheme. Turbine is one of the major components of the scheme, and its function is to convert the energy in falling water to power. It is a prime mover in a hydro power station. The right choice of hydraulic turbine for any SHP site that can match up with varying seasonal water flow is a major way to optimise net power output. The energy estimates and turbine analysis made in this study indicates that optimum electrical energy from SHP can be obtained if designer follows steps described in this study. Inappropriate turbine selection often leads to significant deficit in SHP annual energy production. Results from the study shows that thorough technical knowledge on SHP turbine selection is the only way to optimize energy output from any selected SHP site.

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