PRINT ISSN 1119-8362
Electronic ISSN 1119-8362

Full-text Available Online at
https://www.ajol.info/index.php/jasem
http://www.bioline.org.br/ja

J. Appl. Sci. Environ. Manage.
Vol. 26 (4) 647-654 April 2022

Feasibility of Large-Scale Combined-Cycle Hydroelectric Power Generation at Shiroro Hydroelectric Power Station, Nigeria

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ABSTRACT: This paper focuses on a model for increasing the power generation of a hydroelectric power station using the combined application of hydrokinetic turbines installed at the tailrace of the existing dam. Hydrokinetic turbines will capture additional power from the energy remaining in water currents exiting draft-tube outlets and tailrace of the dam. Two commercially available hydrokinetic turbines of different orientation were used for the analysis to theoretically estimate the increased power generation capability of Shiroro hydropower station using an array of 75, 150, 225 and 300 units. Preliminary results showed that at 50% reliability, combined-cycle hydropower can increase the generation capacity of Shiroro hydropower station by 2.5% and that there is a considerable power generation potentials that can be harnessed to augment existing output from the power station and alleviate the existing power problems in the country.

DOI: **https://dx.doi.org/10.4314/jasem.v26i4.12**

Impact factor: **http://sjifactor.com/passport.php?id=21082**

Google Analytics: https://www.ajol.info/stats/bdf07303d34706088ffffbc8a92c9c1491b12470

Dates: Received: 07 February 2022; Revised: 13 March 2022; Accepted: 07 April 2022

Keywords: power generation, hydrokinetic turbines; tailrace, draft-tube, array, power station

Hydropower (HP), being one of the world's most widely used renewable energy resource, contributing to more than 16% of electricity generation worldwide and about 85% of global renewable electricity plays an important role in enabling countries and communities around the world meet their power and water needs (OECD/IEA, 2017; HydroTasmania, 2006). In Nigeria, hydropower has the second highest alternative energy potential after solar energy and contributes majorly to the present energy generation of the country. There are three large conventional hydroelectric power stations. The Jebba and Kainji dams have capacities of 570 MW and 760 MW respectively while the Shiroro dam has a capacity of 600 MW. These make the total existing capacity for major hydro power in Nigeria 1,930 MW. To complement the existing capacity, small and mini hydro power schemes with established potentials has been introduced in some parts of the country. In a typical hydropower system, water flows into the turbine chamber through the penstock and gets discharged through the draft tube exit. However, it has been observed that there is still considerable energy in the water exiting the draft tube into the tailrace which can be tapped and harnessed for the generation of additional energy to augment what the power plant is producing. This can be achieved by deploying suitable devices that can extract kinetic energy from the tail water. A typical scheme is through the use of Marine Hydrokinetic Turbines (MHKT). Hydrokinetic energy is the energy that can be captured from flowing water in rivers, canals and man-made water ways. It is a technology that is well suited for rural areas where huge civil works are not required (Ladokun *et al*, 2013).When Marine Hydrokinetic Turbines is deployed at the tailraces of the existing hydropower dams, more kilowatts or megawatts can be generated. This can be coined as combined cycle hydropower (Yue and Packey, 2014). Combined cycle hydropower signifies the combination of the power generated by the stored water released from the reservoir and additional power generated from the 'waste' turbine discharge using kinetic energy turbines. Arango (2011) has done an investigation on the possibility of installing a kinetic energy hydro turbine at the back of existing hydro installations. He stated that the velocity found at the outlet of the powerhouse draft tubes constitutes a loss in conventional hydroelectric systems and exploiting this kinetic energy would allow for the

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maximum use of the flow passing through the conventional turbines. Khan et *al.* (2009) indicated the hydro turbines could potentially be used in conjunction with an existing hydroelectric facility, where the tailrace of a stream can be utilized for capacity augmentation. Yue and Packey (2014) also indicated that it is possible to increase hydropower production by installing hydrokinetic turbines behind existing conventional hydropower stations to establish "combined-cycle hydropower system (CCHS)". This was also demonstrated by Hydro Green Energy (Hydro Green Energy, 2017) in the deploying of one of their hydrokinetic turbine product at the Hydropower station in Hastings, USA. The goal of this work is to evaluate the feasibility of large-scale combined-cycle hydroelectric power generation at Shiroro hydropower station and carry out a theoretical analysis of the additional power yield when hydrokinetic turbines are installed at specific locations of the draft tube exit and tailrace.

MATERIALS AND METHODS

Equation of the combined cycle hydropower can be expressed as: Combined cycle hydropower (CCH) = Hydrostatic power + Hydrokinetic power

Hydrostatic power $\boldsymbol{P} = \eta\rho g \mathbf{Qh}$ (1)
Hydrokinetic power $\boldsymbol{P}_{hk} = \frac{1}{2}\eta\rho \mathbf{N} A v^3$ (2)
CCH $= \rho(g\mathbf{Qh}+\frac{1}{2}\mathbf{N}Av^3)$ (3)

where η is the efficiency of the system, ρ is the mass density of the water in kgm^{-3}; g is the gravitational acceleration in ms^{-2}; $\mathbf{Q}$ is the discharge in m^3s^{-1}; $\mathbf{h}$ is the hydraulic head in m; $\mathbf{N}$ is the number of hydrokinetic turbine units; A is the swept area of the hydrokinetic turbine in m^2 and v is the velocity of flow in ms^{-1}.

Study Area: Shiroro Hydropower Station is one of Nigeria's major hydroelectric power plants located at Shiroro Gorge of River Kaduna on longitude 6.84° and latitude 9.97°. It has four 150 MW hydro-turbine units with a total generation capacity of 600 MW. It has a gross storage capacity of $6.05x10^9$ m^3 and a water surface area of $7x10^9m^3$. It is made of a rock-filled concrete face dam with crest elevation of 385m and width of 7.5m. It has tailrace length of 2100m and width of 75m. It has 8 draft tube gates.

The Shiroro Tail Race: The study focuses on the tail water of the Shiroro hydroelectric power station. The tailrace is the downstream channel that carries water away from a dam or powerhouse. It has a length of 2100 m, width of 75 m and the bottom elevation is 265 m. Eight draft tube exits from 4 draft tube outlets open into the tailrace region. Each draft tube outlet measures 6.64 × 6.25 m.

Resource potentials: A very important step in analyzing the available hydropower resource potential, is to investigate the possible regions of extraction i.e. points that will give higher potentials after the placement of hydrokinetic turbine rotors. Point of extraction should offer the best combination of the following criteria: (Arango, 2011) 9i) (i) velocities should be above 1 m/sec (ii) there should be sufficient depth (iii) there should be ease of access, and (iv) regions prone to large scale hydrodynamic turbulence should be avoided

The four possible regions of extraction are: the draft tube, the tailrace waters, the draft tube exit, and the first section downstream of pier noses combined with the bay outlet area. However, considering the criteria listed above, the draft tube and the section near the bay outlet area could be discounted due to high hydrodynamic fluctuations and limited ease of access to those areas. The draft tube outlet and specific areas in the tailrace are good for introduction of hydrokinetic turbines.

Turbine Discharge at Shiroro dam: The summary of statistics of turbine discharge at Shiroro dam is presented in Table 2. For the 20 years (1990 – 2010) data available for analysis, the peak turbine discharge was 792.45 m^3/s, while the lowest turbine discharge was 20.80 m^3/s. The peak value occurs during the month of August, 2004, while the low turbine discharge occurred in December, 2002. The monthly and annual variation of the turbine discharge is presented in Figure 1 and 2.

Table 2: Turbine discharge at Shiroro hydropower dam (m^3/s) (1990-2010)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	236.99	260.65	255.32	238.34	213.58	231.07	338.20	359.43	339.27	345.93	245.03	225.88
S.D	81.36	71.07	72.44	85.20	79.13	84.18	84.69	140.14	149.38	119.09	121.24	86.59
Skew	0.11	-0.55	-0.30	0.68	0.12	2.41	0.33	1.30	-0.04	-0.26	-0.04	0.04
CV	0.34	0.27	0.28	0.36	0.37	0.36	0.25	0.39	0.44	0.34	0.49	0.38
Max	416.63	390.13	381.98	444.95	407.48	525.85	494.03	792.45	604.63	575.27	504.75	435.86
Min	75.60	99.21	118.17	87.31	35.84	141.63	172.84	127.50	94.33	86.36	22.15	20.80

Source: *Shiroro Hydroelectric Power Station (2010)*

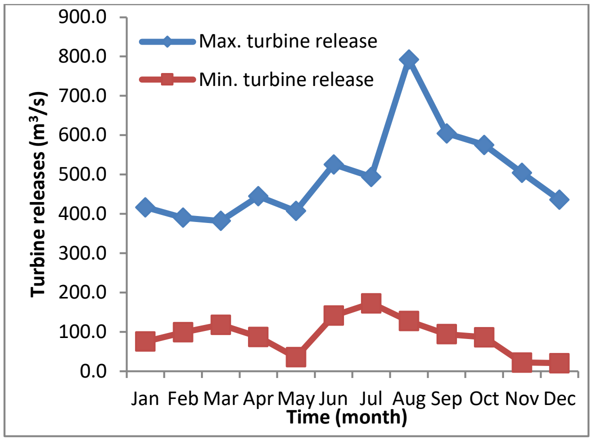

Fig 1: The monthly variation of the turbine discharge

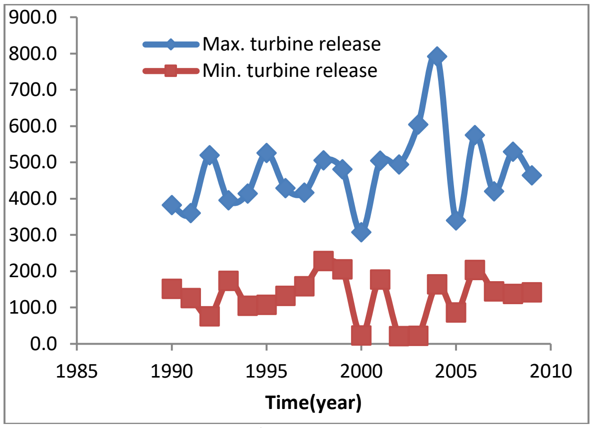

Fig 2: The annual variation of the turbine discharge

The turbine discharge profile for Shiroro hydroelectric station for the selected years of 2008 to 2012 is shown in Figure 3. It can be observed that the turbine discharges vary from month to month across the years. The highest discharges are between the months of July and September while the lowest are recorded between January and April. The chart also shows the trend of the reservoir operations of the station. This gives a hint on the hydrological pattern of the region. Optimum power output can be obtained at those times.

Flow velocity at the regions of interest: The velocity of flow can be calculated from the data of the turbine discharge using the relation;

$$Q = VA \qquad (1)$$

Then,

$$V = \frac{Q}{A} \qquad (2)$$

Where Q = Turbine Discharge (m^3/s); A = Area of flow (m^2); V = Velocity of flow (m/s)

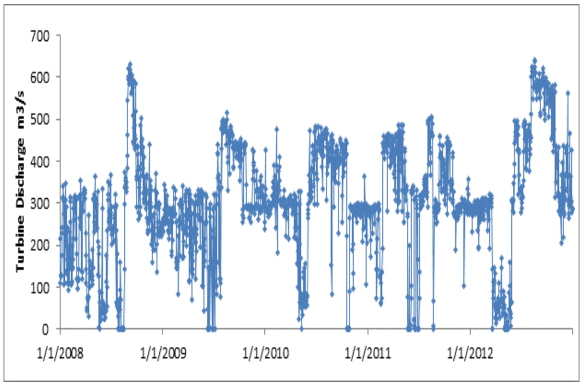

Fig 3: Turbine discharge profile of Shiroro Hydropower Station for the selected years

The estimated flow velocities at the draft tube and the tail race are plotted against time as shown in Figure 4. The velocity of flow of each region is important in determining the quantum of hydrokinetic power that can be obtained and it also depends on the turbine discharge.

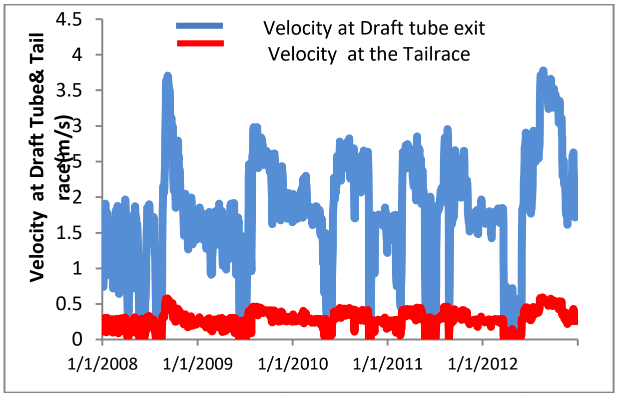

Fig 4: Flow velocity at the draft tube exit and the tailrace for the selected years

Obtainable Power Resource: The power to be tapped from the selected regions of interest can be categorized into two: (i) Theoretical Resource: the gross, naturally available resources of in-stream energy within the area. (ii) Technically recoverable Resource: the technical resource is the theoretical resource constrained by the efficiency of the currently available technology to extract renewable energy from the source.

The theoretical resource can be obtained by making use of the entire areas of the draft tube exit and the tailrace to compute the additional hydrokinetic power that can be generated. Flow area at the Draft tube A_{dt} is given by:

$$A_{dt} = L \times W \qquad (3)$$

Given that the Length of Draft Tube, L = 6.64m; Width of the Draft Tube, W = 6.25m, then

$$A_{dt} = 6.64 \times 6.25 = 41.5\text{m}^2$$

For the four turbine units at Shiroro hydropower station, there are eight (8) outlets at the draft tube exit, and the total area of the draft tube exit is then; $A_{dt} = 8 \times 41.5 = 332\ \text{m}^2$

(i) The theoretical combined cycle hydropower at the draft tube region can be estimated as

$$\eta\rho[\, gQh + {}^{1}\!/_{2}\,(332)v^3\,] \quad (4)$$

Flow area at the tailrace A_{tr} is Length of tailrace water x Height of the tailrace water

$$A_{tr} = L \times W \quad (5)$$

Total length of the tail race is 76 m, Width W is 14.14 m, therefore

$$A_{tr} = 76 \times 14.14 = 1074.64\ \text{m}^2$$

Then, theoretical combined cycle hydropower at the tailrace region can be estimated as

$$\eta\rho[\, gQh + {}^{1}\!/_{2}\,(1074.64)v^3\,] \quad (6)$$

(ii) The technical power resource is obtained by considering the use of two already available commercial kinetic energy hydro turbines. These are the Vertical Axis EnCurrent Turbine and the Horizontal axis Smart Turbine. The vertical turbine selected is the New Energy Corporation's EnCurrent Power Generating System (New Energy Corporation, 2009) shown in Figure 5a. Table 3 presents the specifications of the selected turbine.

Table 3: Specifications of the Vertical EnCurrent turbine (New Energy Corporation, 2009)

Company	**New Energy Corporation Inc.**
Turbine Model	EnCurrent Power Generating System
Type	Vertical axis turbine
Rated Power	25kW at a flow speed of 3m/s for high speed models and 2.6m/s for low speed models
RPM	22.4 rpm
Rotor Diameter	4.8m
Rotor Height	2.4m
Number of Blades	4-5

For the Vertical Axis Turbine, the Area of the turbine A_{vt} = Rotor Width × Rotor Height

$$A_{vt} = D \times H \quad (7)$$

Then, combined cycle hydropower for the vertical axis turbine at the draft tube region can be estimated as:

$$\eta\rho[\, gQh + 1/2A_{vt}V_{dt}^3] \quad (8)$$

Also, combined cycle hydropower for the vertical axis turbine at the tail race region can be estimated as

$$\eta\rho[\, gQh + 1/2A_{vt}V_{tr}^3] \quad (9)$$

The Horizontal axis turbine selected is the Free Flow Power Corporation's Smart Turbine shown in Figure 5b and the specifications of the turbine are presented in Table 4. The area of the Horizontal turbine is given by:

$$A_{HT} = \pi \times \frac{((\text{rotor diameter})^2)}{4} \quad (10)$$

Then, the combined cycle hydropower for the vertical axis turbine at the draft tube region can be estimated as:

$$\eta\rho[\, gQh + 1/2A_{HT}V_{dt}^3] \quad (11)$$

Also, the combined cycle hydropower for the vertical axis turbine at the tail race region can be estimated as:

$$\eta\rho[\, gQh + 1/2A_{HT}V_{tr}^3] \quad (12)$$

RESULTS AND DISCUSSION

The theoretical hydrokinetic power depends on the velocity of flow and the cross-sectional area of flow. The variations in the power outputs from draft tube and tail race as shown in Figure 6 are due to differences in cross-sectional areas at the draft tube and the tail race for a constant turbine discharge. Presented in Figure 7 is the comparison between the vertical type hydrokinetic turbine system and its horizontal counterpart. It can be observed that the power curves follow the same profile. The vertical type turbines have higher hydrokinetic power magnitudes that the horizontal turbine system.

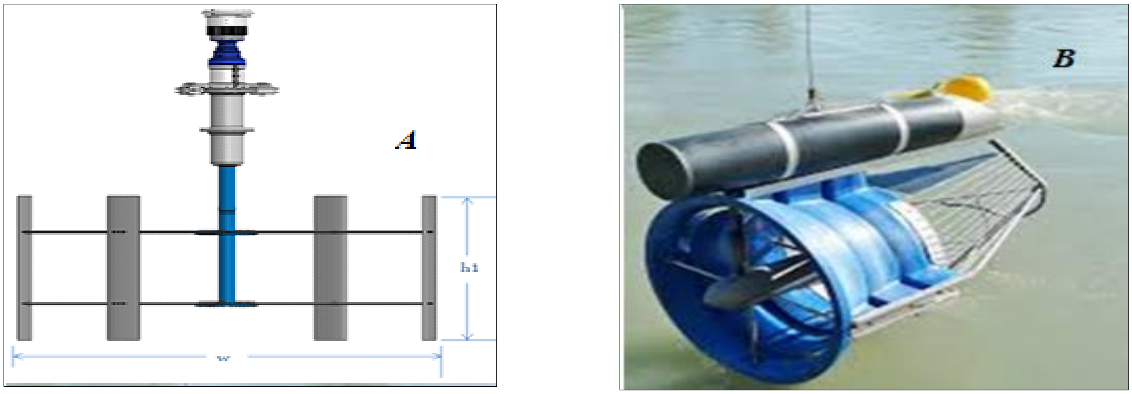

Fig 5a & b: EnCurrent Vertical Axis Turbine and Horizontal Smart Turbine (Free Flow Power Corporation, 2010) (New Energy Corporation, 2009)

Table 4: Specifications of the Horizontal Smart Turbine (Free Flow Power Corporation, 2010)

Company	**Free Flow Power Corporation (FFP)**
Turbine Model	Smart Turbine TM
Type	Shrouded Horizontal Axis Turbine
Rated Power	40kW at a flow speed of 3m/s; cut-in speed 1m/s; cut-out speed 4m/s
RPM	38 rpm at 2.25m/s, less than 70 at 4m/s
Rotor Diameter	3.0m
Number of Blades	7

Again it can be seen that the power generated increases considerably in July and gradually decays as the year wears out. Having seen that the vertical axis turbines have better magnitude, Figure 8 presents the power magnitudes obtained for the equation for the vertical axis EnCurrent turbine. It can also be observed that the power that can be obtained at the draft tube exit is more than that of the tailrace.

To determine of the combined cycle hydropower estimates, i.e. the combination of the power produced conventionally by the station and the hydrokinetic power estimates, flow duration analysis percentage level of reliabilities was used. The dependable turbine discharges at 50%, 60%, 75%, 90%, 95% and 99% exceedence probability levels was obtained and the corresponding hydropower outputs and hydrokinetic estimates for the region of extraction are presented in Table 5.

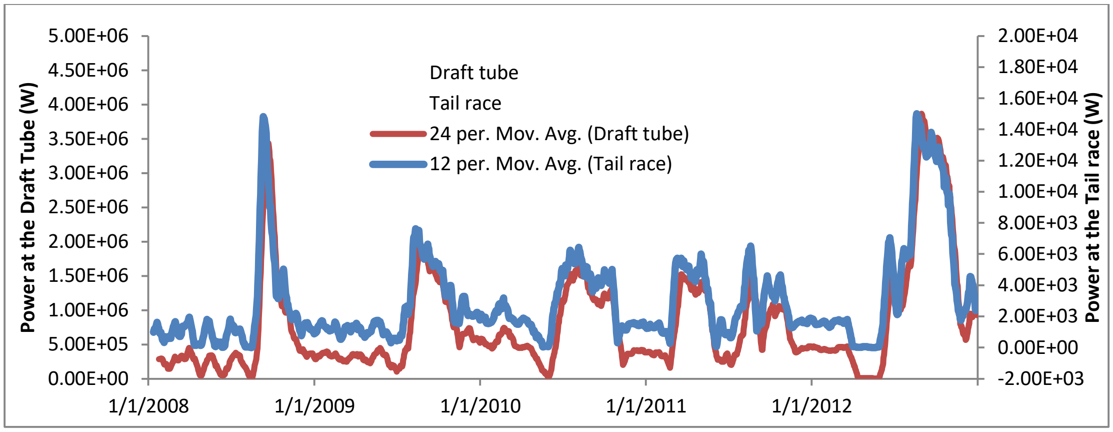

Fig 6: Estimated theoretical power obtainable at Shiroro hydropower station

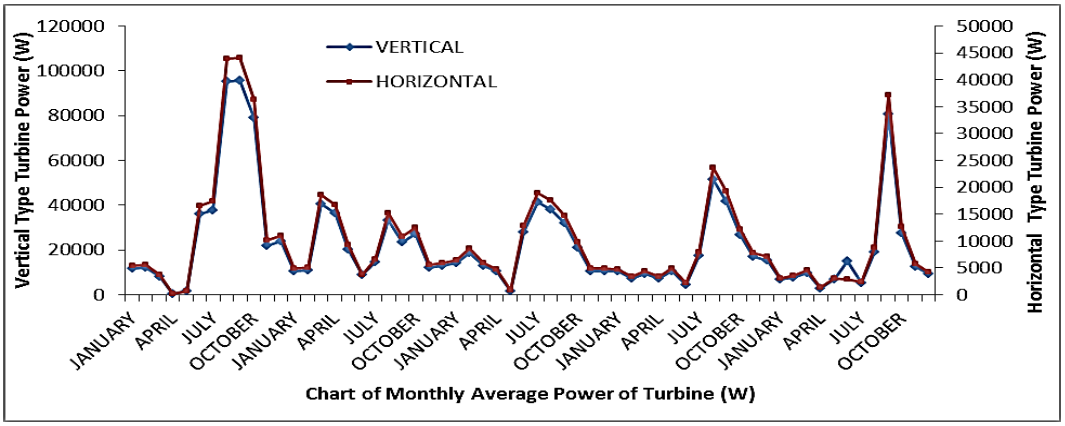

Fig 7: Monthly average power for vertical and horizontal type turbines

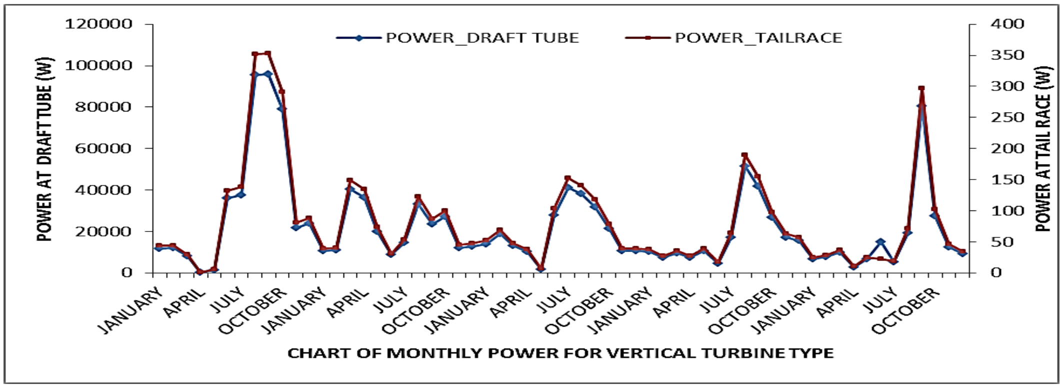

Fig 8: Monthly average power for draft tube exit and tailrace locations

Table 5: Turbine discharge and corresponding hydrokinetic estimates

Level of Reliabilities (%)	50	60	75	90	95	99
Turbine Discharge (m^3/s)	300	280	220	160	120	10
Energy Output (MW)	228	213	168	122	92	8
Probable Hydrokinetic Power at the Draft Tube (MW)	5.88	4.78	2.32	0.89	0.38	0.22
Total Combined Cycle Hydroelectric power	233.88	217.78	170.32	122.89	92.38	8.22
% Increase	2.5	2.2	1.4	0.7	0.4	0.27

It is estimated that between 0.27 to 2.5% increases can be obtained in the power generation output at Shiroro when a single hydrokinetic turbine is installed. However, the technology of kinetic energy turbines allow for deployment in an array format. The combined cycle hydropower outputs for various turbine arrays are presented in Figures 9 - 11.

The arrays presented are for both the vertical axis turbines and for the horizontal axis turbines at the draft tube region of extraction and under different reliabilities. For example, for an array of 150 vertical axis turbines set at the draft tube exit of a hydropower system, the magnitude of additional power produced is 2MW for 50% reliability. This means that for a selected period of time, the probable magnitude of additional hydrokinetic power that can be obtained within the specific hydraulic geometries is that value at half of the time considered. This is its capacity factor.

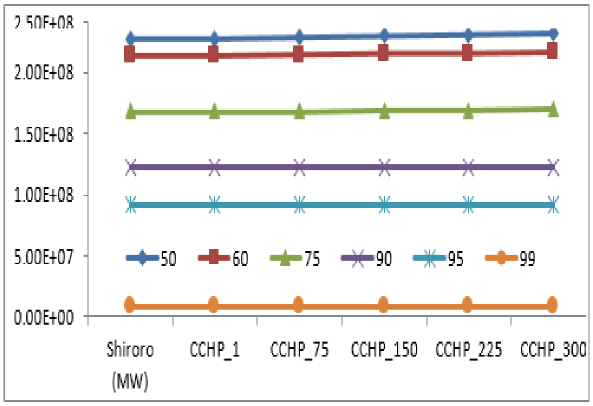

Fig 9: The array for combined cycle hydropower at the draft tube region of extraction under different reliabilities

Figures 10 present the combined-cycle hydropower generated when an increasing array of vertical axis hydrokinetic turbines are deployed.

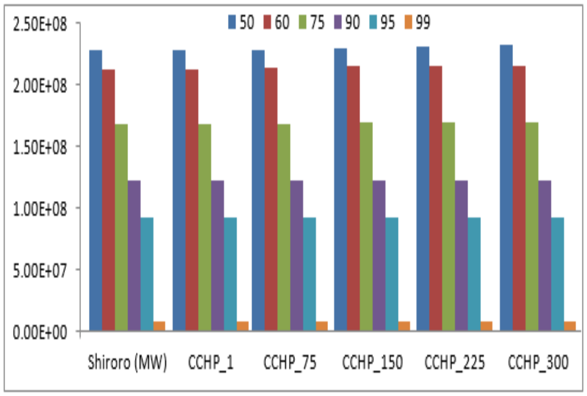

Fig 10: The array for combined cycle hydropower for vertical axis turbines at the draft tube region of extraction under different reliabilities

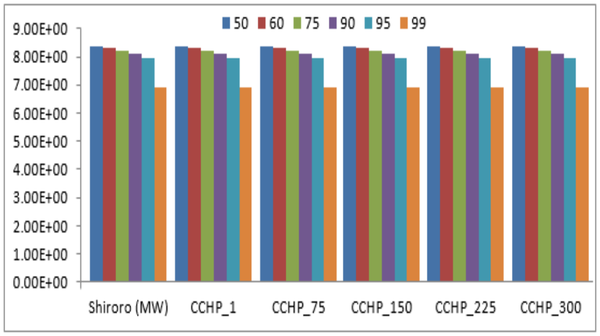

Fig 11: The array for combined cycle hydropower for horizontal axis turbines at the draft tube region of extraction under different reliabilities

The increase in power generated is minimal for the lower number of deployed turbine but increases as the numbers of turbines set in array increases. Figures 11 present the combined-cycle hydropower generated when horizontal axis hydrokinetic turbines are deployed in an increasing array. The power generated rises from the array with minimal number of deployed turbines to the ones with higher numbers thus producing better output power. Testing statistically for significant difference between the original power generated and the power produced by the combined cycle hydropower using the t-test, it can be observed that there is no significant difference at $\boldsymbol{\alpha} = 0.05$, but a rather significant improvement noticeable at $\boldsymbol{\alpha} = 0.01$ for both the vertical and horizontal axis turbine models selected at the various levels of reliabilities. Figure 6 and 7 presents this. Table 8 presents the monthly average power produced by one vertical axis turbine at the draft tube exit for the selected five year period. Multiplying this by the time period gives Table 9 which is the value for the energy produced. Presently, Power distribution companies in Nigeria charges ₦24.97 per kWh for R2 residential areas (NERC, 2017) in Ibadan Electricity Distribution Company (IBEDC). The total amount of income generated by deploying only one hydrokinetic turbine can be estimated and this is presented in Table 9. From the chart, it can be seen that income to the tune of N7 million per turbine can be realized per year by Generating companies (GENCOs). If we consider deploying an array of 300 vertical axis turbines, as the Shiroro tail water can allow, substantial amount to the tune of over N2 billion can be earned (excluding installation, maintenance & depreciation).

Table 6: Paired Sample Test for vertical axis combined cycle hydropower

		Paired Differences							
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Pair 1	Initial Generation - One HKT added	-5.49E3	5656.47632	2309.24679	-11428.5368	443.67885	-2.378	5	0.063
Pair 2	Initial Generation - 75 HKT added	-4.119E5	4.24249E5	1.73199E5	-8.57141E5	33303.28874	-2.378	5	0.063
Pair 3	Initial Generation - 150 HKT added	-8.238E5	8.48499E5	3.46398E5	-1.71428E6	66606.56174	-2.378	5	0.063
Pair 4	Initial Generation - 225 HKT added	-1.236E6	1.27275E6	5.19597E5	-2.57142E6	99909.85048	-2.378	5	0.063
Pair 5	Initial Generation - 300 HKT added	-1.647E6	1.69700E6	6.92796E5	-3.42857E6	1.33213E5	-2.378	5	0.063

Table 7: Paired Sample Test for horizontal axis combined cycle hydropower

		Paired Differences							
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Pair 1	Initial Generation - One HKT added	-2.528E3	2603.69254	1062.95303	-5260.41641	204.39908	-2.378	5	0.063
Pair 2	Initial Generation - 75 HKT added	-3.792E5	3.90552E5	1.59442E5	-7.89061E5	30658.08417	-2.378	5	0.063
Pair 3	Initial Generation - 150 HKT added	-5.688E5	5.85829E5	2.39164E5	-1.18359E6	45987.12952	-2.378	5	0.063
Pair 4	Initial Generation - 225 HKT added	-7.584E5	7.81105E5	3.18885E5	-1.57812E6	61316.18769	-2.378	5	0.063
Pair 5	Initial Generation - 300 HKT added	-9.479E5	9.76393E5	3.98611E5	-1.97266E6	76667.08593	-2.378	5	0.063

Table 8: Monthly average energy produced and energy costs by one vertical axis hydrokinetic turbine at the draft tube exit

Month	**2012**	**₦**	**2011**	**₦**	**2010**	**₦**	**2009**	**₦**	**2008**	**₦**
Jan	8556.28	213,650	7670	191,519	10096.9	252,120	7499.48	187,261	4850.7	121,121
Feb	8643.97	215,840	7852.8	196,082	13483.7	336,686	5321.26	132,871	5638.9	140,804
Mar	5785.64	144,467	29088.3	726,334	9368.3	233,926	6828.77	170,514	7107.4	177,472
Apr	180.606	4,509	26192.6	654,028	7482.7	186,843	5295.34	132,224	2008.4	50,149
May	1074.27	26,824	14468.9	361,289	1241.3	30,994	7549.23	188,504	4833.4	120,690
Jun	25907.3	646,904	6340.6	158,326	20136.0	502,796	3321.23	82,931	10846	270,819
Jul	27098.2	676,641	10388.3	259,396	29714.6	741,974	12419.4	310,111	3780.3	94,392
Aug	68674.4	1,714,799	23881.7	596,325	27503.8	686,769	36970.7	923,158	13860	346,096
Sept	68954.8	1,721,800	16938.3	422,949	23010.7	574,577	30189.8	753,839	58042	1,449,31
Oct	56811.9	1,418,592	19622.6	489,976	15302.6	382,105	19157.8	478,370	19894	496,751
Nov	15779.9	394,021	8707.9	217,437	7553.8	188,618	12262.2	306,187	9066.4	226,387
Dec	17126.0	427,637	9332.1	233,023	7731.1	193,046	11154.5	278,528	6738.5	168,261
		7,605,689		**4,506,690**		**4,310,458**		**3,944,504**		**3,662,262**

Also it can be seen that at 50% reliability, the combined cycle hydropower system can generate extra 4 MW in addition to the 228 MW expected from the conventional hydropower scheme. If an average household uses an estimated 250 kWh, then a total of 138,240 homes can be supplied with 24 hours electricity all year round with an array of 300 vertical axis hydrokinetic power at minimal cost and at minimal interference with existing infrastructure.

Conclusion: The assessment of the potential and the feasibility of obtaining increased hydropower production from Shiroro hydroelectric power station by installing hydrokinetic turbines at the tailrace of the existing dam have been shown to be feasible and technologically viable. The commercially available vertical axis turbines can generate better hydrokinetic power than the horizontal axis type for the regions of extraction. Hydrokinetic power of about 4.75MW can be theoretically achieved and over 6MW can be technically achieved based on the dimensions of a commercially available turbine. At 50% reliability, combined-cycle hydropower can increase the generation capacity of Shiroro hydropower station by 2.5% and the more hydrokinetic turbines in array are deployed, the more the capacity for the combined-cycle hydropower scheme to generate more power.

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