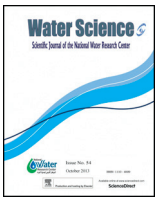
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Research Article

Resource assessment and feasibility study for the generation of hydrokinetic power in the tailwaters of selected hydropower stations in Nigeria

Laniyi L. Ladokun [a,*], Bolaji F. Sule [b], Kajogbola R. Ajao [c], Adeniyi G. Adeogun [d]

[a] *National Centre for Hydropower Research and Development, Energy Commission of Nigeria, P.M.B. 1515, University of Ilorin, Ilorin, Kwara State, Nigeria*

[b] *Department of Water Resources & Environmental Engineering, University of Ilorin, Ilorin, Nigeria*

[c] *Department of Mechanical Engineering, University of Ilorin, Ilorin, Nigeria*

[d] *Department of Civil Engineering, Kwara State University, Malete, Kwara State, Nigeria*

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Abstract

This paper focuses on assessing the potential and feasibility of increasing the hydropower production of Nigeria's three main hydropower stations by installing hydrokinetic turbines behind the existing dams. The hydrokinetic turbines will capture additional power from the energy remaining in water currents exiting draft-tube outlets and tailraces of the dams. A 2.54 m^2 prototype hydrokinetic turbine system being developed by the National Centre for Hydropower Research and Development, Nigeria was used to theoretically estimate the increased power generation capability of the stations. Preliminary results showed that there are considerable potentials in the range of kilowatts and megawatts in each hydropower station to augment the existing power infrastructure and this can be harnessed to alleviate the existing power problems in the country. It may also be an additional way of generating clean energy to mitigate the effect of climate change.

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Keywords: Hydrokinetic; Hydropower; Turbine discharge; Tailwaters; Draft tube outlet

* Corresponding author.
E-mail addresses: niyiladokun@gmail.com (L.L. Ladokun), bfsule@unilorin.edu.ng (B.F. Sule), ajaomech@unilorin.edu.ng (K.R. Ajao), adeniyi.adeogun@kwasu.edu.ng (A.G. Adeogun).

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1. Introduction

Hydropower, 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 and plays an important role in enabling countries and communities around the world meet their power and water needs (Hydro Tasmania, 2006; OECD/IEA, 2017). In Nigeria, energy obtained from the 3 major hydropower stations at Kainji, Jebba and Shiroro and from some smaller schemes presently produces one-fifth of the total energy generated (Index Mundi, 2017; Trading Economics, 2017). However, with the population running to 180 million and the gap between the energy demands and supply increasing, an insight into various and alternate ways of increasing the available power and improving the energy mix is inevitable. A way of augmenting and increasing the amount of energy obtained from the existing hydropower facility is through the generation of additional power from the turbine discharge and tailwaters of the existing hydropower stations. This can be done through the deployment of an array of kinetic energy turbines (hydrokinetic turbines HKT) at strategic areas in the system.

Hydrokinetic (In Stream, or water current) energy conversion involves the utilization of the kinetic energy of rivers, streams, tidal currents or other man-made waterways for generation of electric power without impounding or diverting the flow of the water resource. Unlike traditional hydropower which uses the potential energy possessed by a body of water because of its height ('head'), hydrokinetic devices employ the available energy in the velocity of a stream to turn turbines. The principle of operation is analogous to that of wind turbines, though they capture energy through the process of hydrodynamic, rather than aerodynamic, lift or drag (Ladokun et al., 2013). Power extracted from a hydrokinetic turbine can be obtained using the expression

$$P = \frac{1}{2}\rho \cup_o{}^3 \eta Cp N A_t \tag{1}$$

where P denotes the recoverable power, A_t denotes cross-sectional area of the fluid or swept area of the turbine, ρ denotes water density, and $\cup_o$ denotes velocity magnitude, ηCp is the product of the efficiency and the power coefficient and N is the number of turbines in the river segment.

Hydrokinetic turbines are rotary engines that convert the energy of a moving stream of water into mechanical energy under the micro-hydro range for ultra-low head applications. They are reaction type turbines which use both velocity and pressure forces to produce power. Fig. 1 presents the various types of hydrokinetic turbines.

Hydrokinetic turbine systems can be used to harvest extra energy from the spent waters of the hydropower system in a combined-cycle hydropower arrangement by locating the HKTs directly behind the turbine of the existing conventional hydropower facilities or placing the HKTs in the vicinity of the powerhouses.

Power from the scheme is obtained by the expression:

$$\textit{Total Power} = \textit{Hydrostatic Power}\,(\eta\rho \mathrm{Qgh}) + \textit{Hydrokinetic Power}\,(\tfrac{1}{2}\eta\rho \mathrm{Av}^3) \tag{2}$$

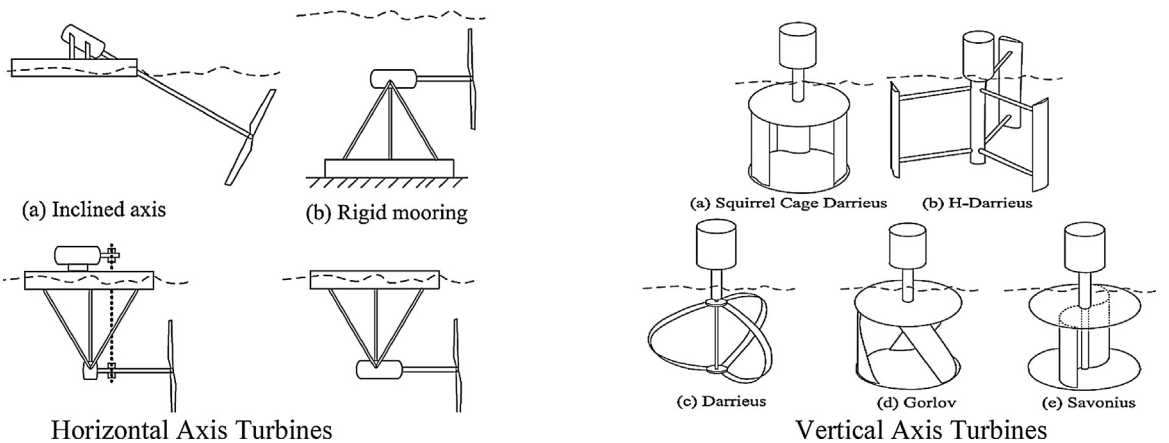


Fig. 1. Horizontal and vertical axis hydrokinetic turbines.

Source: Khan et al. (2009).

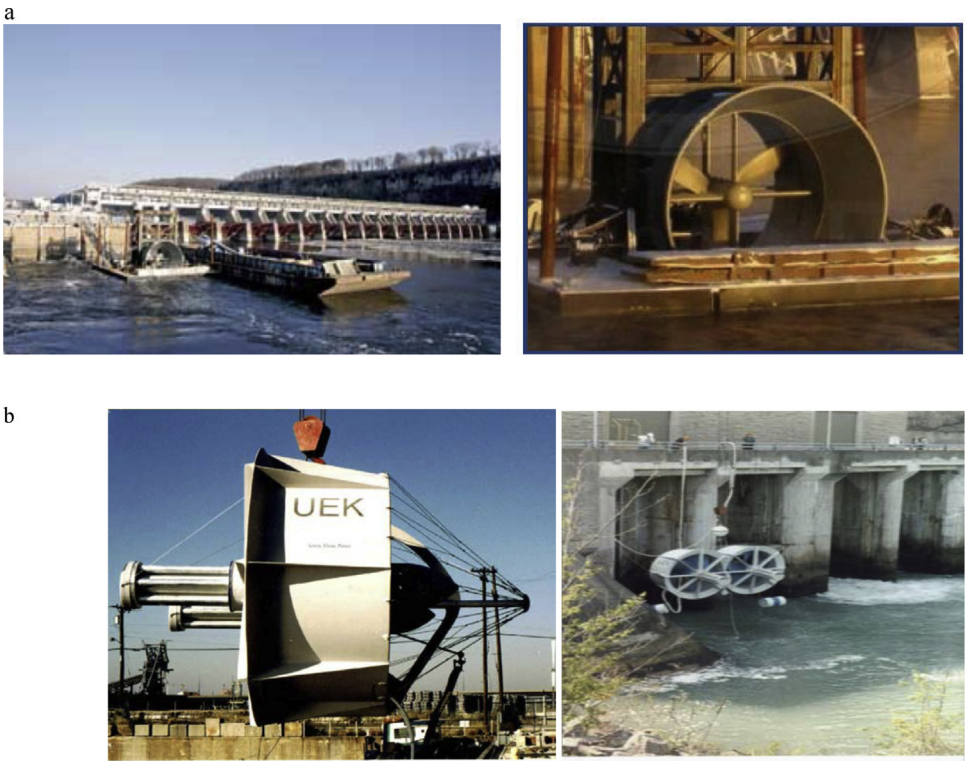


Fig. 2. (a) Palates of the hydropower dam at Hastings which has been deployed with hydrokinetic turbines (Hydro Green Energy, 2017b). (b) Twin UEK turbine installed at Ontario Hydro (Atlantic Renewable Energy, 2017; IWP&DC, 2006).

where, Power in watts; η is the dimensionless efficiency of turbine; ρ is the density of water in kg per m^3; Q is the flow in m^3 per second; g is the acceleration due to gravity; h is the height difference between intake and outlet.

Arango (2011) has investigated the scheme by analysing the stretch of the Columbia River downstream from the Wanapum and Priest Rapids Dams to assess the feasibility of introducing hydrokinetic turbines in the tailwaters of the dams for extracting power. Four sites were considered as being feasible for use some existing turbine concepts were selected to determine their hydrodynamic outputs under varying water depths and flow velocities. The study results showed that each turbine can extract the power from tailrace waters at certain proportions of their designed capacities at each site.

Another application of this scheme is in the deployment of hydrokinetic turbines at the tailrace of the hydropower station in Hastings, USA (Hydro Green Energy, 2017a). This is shown in Fig. 2a. It involves the installation of two turbines downstream of an existing 4.4 MW run-of-river hydropower plant. The equipment is expected to generate as much as 250 kW, representing a 5.7% increase in renewable energy generation at the site.

Twin UEK Turbines were also installed at Ontario Hydro as seen in Fig. 2b (Atlantic Renewable Energy, 2017; IWP&DC, 2006).

The purpose of this paper is to assess the potential of the tailwaters of Nigeria's major hydropower stations for the generation of hydrokinetic power to augment the existing infrastructure.

2. Materials and methods

The three major Hydroelectric Power Stations (HEPS) in Nigeria i.e. the Kainji HEPS, Jebba HEPS and the Shiroro HEPS located at the North-central region were selected for the study because of their capacity and contribution to the nation's overall power production. The study was conducted by carrying out reconnaissance surveys and obtaining of documented and in situ data peculiar to each of the hydropower scheme. The study was then approached in three main



Fig. 3. Plate and sky view of Kainji Hydropower Station.

Table 1
Engineering specifications of Kainji Hydropower Station.

S/No	Engineering characteristics	Specifications
1	Crest elevation of dam	145.0 m
2	Max water surface elevation	141.9 m
3	Hydraulic head	24–42.2 m
4	Maximum tailrace level	129.0 m
5	Spillway gates (dimension)	1.53 m × 15.3 m
6	Number and type of spillway gates	4 radial gates
7	Penstocks	Twelve steel lined (8.55 m diameter)
8	Turbine type	Kaplan and propeller type turbines
9	Number of turbines	8 (6 Kaplan and 2 propeller types)
10	Power installation capacity	Kaplan (520 MW) propeller (240 MW)
11	Unit speed	107.2–115 rpm

Source: Kainji HEPS (2010).

steps. One is the identification of possible sites along the tailraces of the three HEPS being considered. This shall be followed by the resource assessment of the schemes and lastly the estimated power obtained.

2.1. Description of the study area

2.1.1. The Kainji Hydropower Station

This is located on latitude 10° 08′ N and longitude 4° 37′ E along the course of River Niger, North-central Nigeria. It is an earth dam with a 66 m high concrete centre structure housing the hydroelectric turbines. The Kainji reservoir is about 135 km long and about 30 km across at its widest point with a surface area of 1250 km^2. An average daily discharge of 2280 m^3/s is required to sustain full generating capacity of 760 MW using eight Kaplan type turbine generation units. Fig. 3 presents a plate of the Kainji Hydropower Station and Table 1 presents other relevant engineering specifications.

2.1.2. The Jebba Hydroelectric Station

This is located on latitude 9° 08′ N and longitude 4° 49′ E along the course of River Niger, and some 100 km downstream of the Kainji Hydropower Station in Niger State. It has reservoir surface area of 270 km^2 and is about 100 km long, with a width varying from 2 to 5 km. Six units of fixed blade propeller type turbines are installed with rated total output of 560 MW. Fig. 4 presents the plate and aerial view of the Jebba Hydropower Station and Table 2 shows the power installation specifications and other relevant engineering specifications.

2.1.3. The Shiroro Hydropower Station

This was built on River Kaduna, one of the principal tributaries of River Niger with its source from Plateau Mountains. The station is 550 m downstream of the confluence with the Dinya River. The reservoir has a total surface area of about



Fig. 4. Plate and sky view of the Jebba Hydropower Station.

Table 2
Engineering specifications of Jebba Hydropower Station.

S/No.	Engineering characteristics	Specifications
1	Crest elevation of dam	108.0 m
2	Max water surface elevation	103.0 m
3	Hydraulic head	27.6–29.3 m
4	Maximum tailrace Level	74.88 m
5	Spillway gates (dimension)	9.5 × 12.0 m
6	Number and types of spillways	6 underflow with flip bucket; radial gates
7	Penstocks	6 steel lined, 10 m diameter
8	Turbine type	Fixed blade, propeller type
9	Number of turbines	6
10	Power installation capacity	570 MW (each with 96.4 MW rated output)
11	Unit speed	93.75 rpm

Source: Jebba HEPS (2010).



Fig. 5. Plate and sky view of Shiroro Hydropower Station.

320 km^2 at elevation 382 m. 4 units of 150 MW gives the estimated installed capacity as 600 MW. Fig. 5 presents the plate and skyview of the Shiroro Hydropower Station and Table 3 shows the power installation specifications and other relevant engineering specifications.

2.2. *Identification of regions of extraction*

The focus of hydrokinetic energy extraction is the water leaving the runner in the power house and flowing on to the tailrace. It is of interest to note the points/regions with maximum relative velocity and absolute pressure where the hydrokinetic turbine can be deployed specifically and likewise areas of least turbulence.

Table 3
Engineering specifications of Shiroro Hydropower Station.

S/No.	Engineering characteristics	Specifications
1	Crest elevation of dam	387.0 m (including parapet)
2	Max water surface elevation	382.0 m
3	Hydraulic head	97 m
4	Maximum tailrace Level	74.88 m
5	Spillway gates (dimension)	15 m wide × 16.65 m high
6	Number and types of spillways	4 concrete Ogee with flip buckets and plunge energy dissipater
7	Penstocks	4 steel lined, 6.33 m diameter
8	Turbine type	Propeller type
9	Number of turbines	4
10	Power installation capacity	600 MW (4 × 150 MW units)
11	Unit speed	93.75 rpm

Source: Shiroro HEPS (2010).

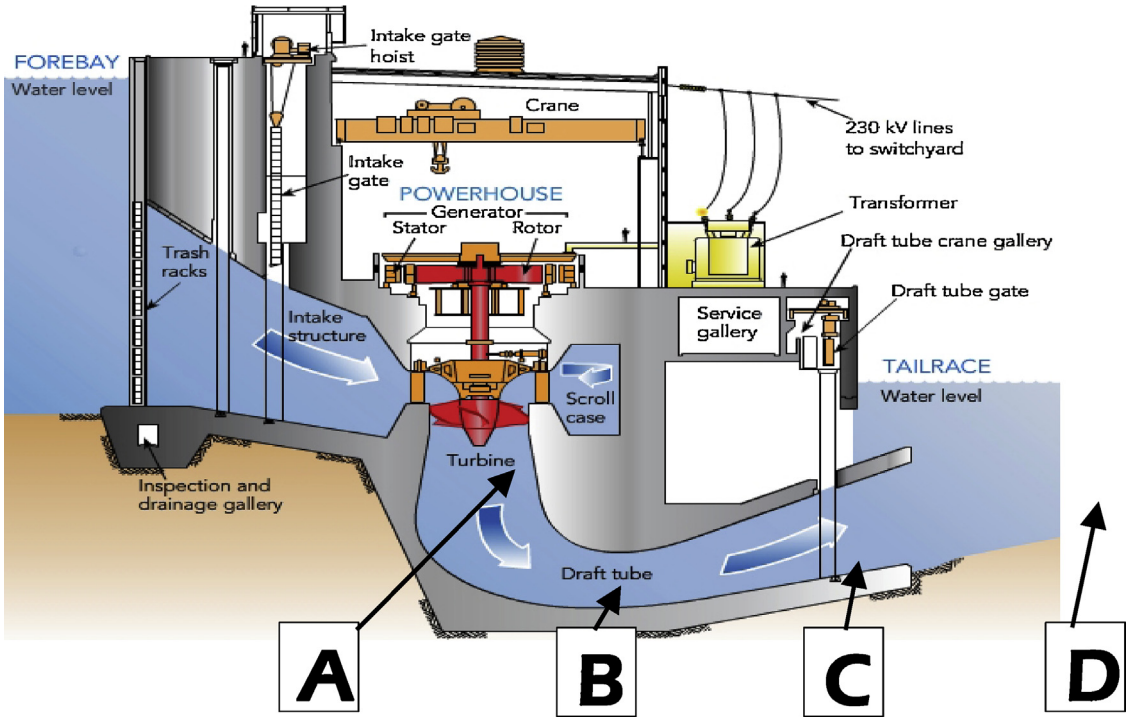


Fig. 6. Schematic of hydropower station showing areas of interest for hydrokinetic power extraction.
Source: Manitoba Hydro (2017).

From literature (Arango, 2011; Cengel and Cimbala, 2006), one can readily divide the possible regions of hydrokinetic energy extraction as the following regions: beginning from the Last Circular Section Downstream of the Runner (region – A), Midway Thru the Elbow (region – B), 1st Section Downstream of Pier Noses combined with the Bay Outlet Area (region – C), and unto the tailrace (region – D).

However, for this study the last two regions of the Outlet areas and the tailraces (regions C & D) shall be our focus for hydrokinetic extraction. The other two regions (A & B) involve much engineering reconstruction which may alter the original HEPS design considerations and generate adverse effects on the overall operation of the plant. Much more, the hydraulic head measurements for conventional hydropower operations are taken from the draft tube exit; hence any alteration there shall affect the output power. Regions A & B shall be for another study for future designs of hydropower stations with facilities for hydrokinetic power. Fig. 6 presents the regions of focus.

Table 4
Statistics of the turbine discharge at Kainji hydropower dam (m^3/s) (1970–2010).

Month	January	February	March	April	May	June	July	August	September	October	November	December
Mean	784.16	813.77	747.86	793.90	720.41	666.18	632.00	709.35	746.30	752.98	740.50	766.69
Max	1234.43	1431.96	1203.41	1345.23	1176.13	1026.62	1060.00	1445.34	1396.60	1289.02	1248.93	1401.94
Min	377.06	405.22	404.27	416.17	404.79	337.31	206.42	203.32	300.60	380.23	198.27	382.77

Source: Kainji Hydroelectric Power Station (2010).

Table 5
Statistics of the turbine discharge at Jebba hydropower dam (m^3/s) (1984–2010).

Month	January	February	March	April	May	June	July	August	September	October	November	December
Mean	1092.40	1019.65	930.00	922.54	860.04	824.15	767.27	997.15	1319.23	1314.31	1037.65	1014.57
Max	1575.00	1643.00	1466.00	1672.00	1383.00	1340.00	1556.00	1927.00	2079.00	2143.00	1655.00	1606.00
Min	585.00	376.00	425.00	232.00	451.00	362.00	328.00	366.00	633.00	685.00	479.00	514.00

Source: Jebba Hydroelectric Power Station (2010).

Table 6
Statistics of the turbine discharge at Shiroro hydropower dam (m^3/s) (1990–2010).

Month	January	February	March	April	May	June	July	August	September	October	November	December
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
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).

2.3. Resource potentials

The turbine discharge history of the three stations aided in the computation of the estimated hydrokinetic power that can be obtained from them. The summaries of statistics of turbine discharges at the stations are presented in Tables 4–6. During the 27 years of operation under consideration for this work (1984–2010), the peak average turbine discharge was 814 m^3/s for Kainji and this occurred in February; 1319 m^3/s was obtained for Jebba station and it occurred in September and a comparatively lower 359.43 m^3/s for Shiroro station, occurring in August. The monthly and annual variations of the turbine discharges are presented in Figs. 7–9 respectively. It shows a gradual increase of turbine operation from 1990 for Kainji, 1987 for Jebba and a fluctuating trend for Shiroro, rising in 1990, 2000 and 2005. The fluctuation in the pattern of releases might be connected to reservoir inflow pattern which depends on seasonal variation in rainfall and other climatic factors at the hydropower stations. Thus, increase in the discharge trends means greater hydrokinetic power possibility from the dams.

2.4. Flow velocity estimates in the regions

Estimated power that can be harvested using hydrokinetic turbines can be computed by first obtaining the areas of the regions under focus and then obtaining the velocity using the volumetric flow rate expression:

$$Q = A.V \tag{3}$$

$$V = \frac{Q}{A} \tag{4}$$

where Q is the volumetric flow rate (discharge), A is the cross-sectional area and V is the flow velocity. Cross-sectional areas of the regions of interest in the three hydropower stations are computed and presented in Table 7. It is of note that the volume flow rate at the draft tube bay outlet is different from the flow rate as the tail waters move a distance away from the outlet along the tailraces. This is because the tailraces do not often have uniform dimensions. Cross section of draft tube bay outlet areas (A) is taken as circular while the tailraces (region B) are taken as rectangular with the

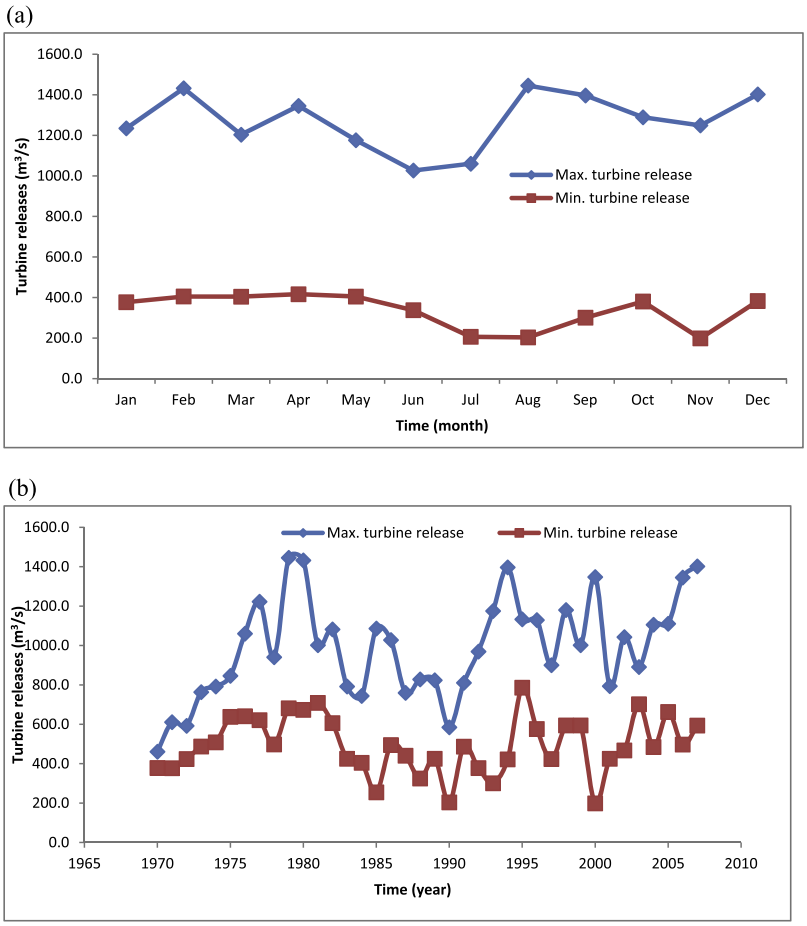


Fig. 7. (a & b) The monthly and annual variation of the turbine discharge at Kainji HEPS (1970–2010).

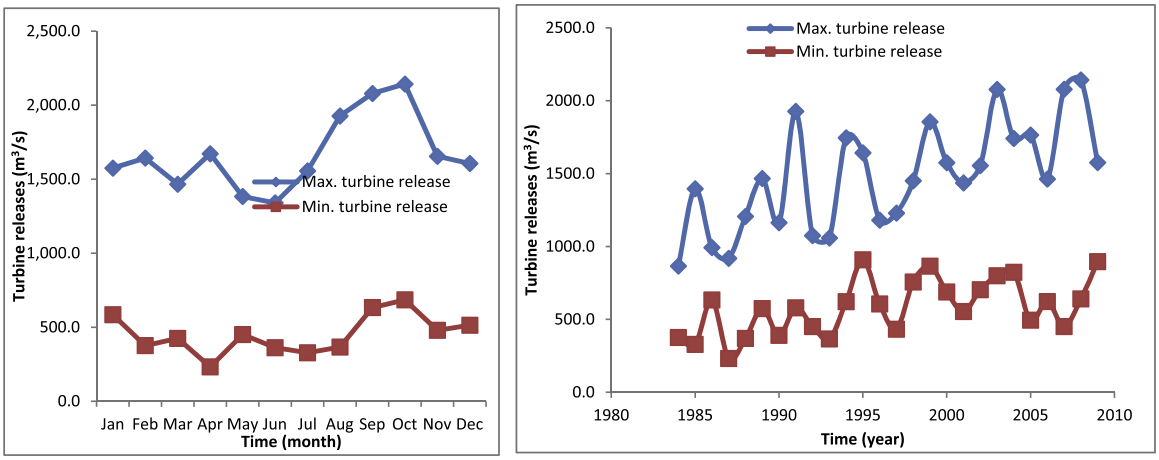


Fig. 8. (a & b) The monthly and annual variation of the turbine discharge at Jebba HEPS (1984–2010).

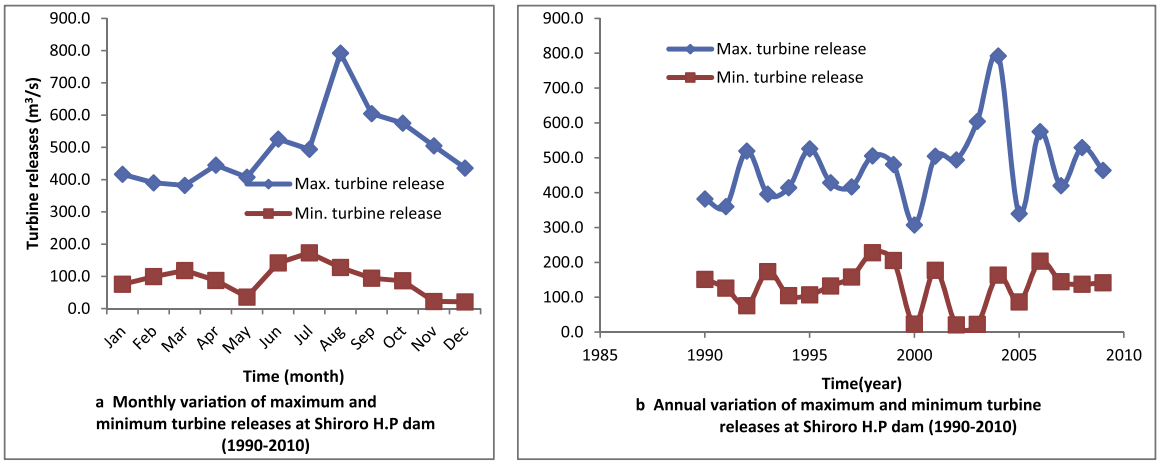


Fig. 9. (a & b) The monthly and annual variation of the turbine discharge at Shiroro HEPS (1990–2010).

Table 7
Areas (m^2) of the regions of focus in the hydropower dams.

Region of focus	Kainji HEPS	Jebba HEPS	Shiroro HEPS
Area of region A – draft tube exit area	85.5 (est. of a unit)	88.0 (est. of a unit)	83.0 (est. of a unit)
Area of region B – tailrace	17,678.53	14,369.39	19,973.25

Table 8
Turbine discharge (m^3/s) and estimated flow velocities (m/s) in Kainji HEPS.

Month	January	February	March	April	May	June	July	August	September	October	November	December
Mean discharge	784.16	813.77	747.86	793.90	720.41	666.18	632.00	709.35	746.30	752.98	740.50	766.69
Velocity_A	9.171	9.517	8.747	9.285	8.426	7.792	7.392	8.296	8.728	8.806	8.660	8.967
Velocity_B	1.15	1.19	1.09	1.16	1.05	0.97	0.92	1.04	1.09	1.10	1.08	1.12

Table 9
Turbine discharge (m^3/s) and estimated flow velocities (m/s) in Jebba HEPS.

Month	January	February	March	April	May	June	July	August	September	October	November	December
Mean discharge	1092.40	1019.65	930.00	922.54	860.04	824.15	767.27	997.15	1319.23	1314.31	1037.65	1014.57
Velocity_A	12.413	11.587	10.591	10.483	9.773	9.365	8.718	11.331	14.991	14.935	11.791	11.529
Velocity_B	2.07	1.93	1.76	1.75	1.63	1.56	1.45	1.89	2.50	2.49	1.97	1.92

Table 10
Turbine discharge (m^3/s) and estimated flow velocities (m/s) in Shiroro HEPS.

Month	January	February	March	April	May	June	July	August	September	October	November	December
Mean discharge	236.99	260.65	255.32	238.34	213.58	231.07	338.20	359.43	339.27	345.93	245.03	225.88
Velocity_A	2.86	3.14	3.08	2.87	2.57	2.78	4.07	4.33	4.09	4.17	2.95	2.72
Velocity_B	0.71	0.79	0.77	0.72	0.64	0.70	1.02	1.08	1.02	1.04	0.74	0.68

average tailrace water level as the height. Flow velocities for regions A were obtained by application of Eq. (4). Flow velocities for region B are obtained by computing the total bay outlet area for each HEPS at a distance of 1 km away from the draft tube exit. Respective flow velocities within the focused regions are presented in Tables 8–10. Turbine Discharge and Estimated Flow Velocities of the three HEPS at their tailraces are presented in Figs. 10–12.

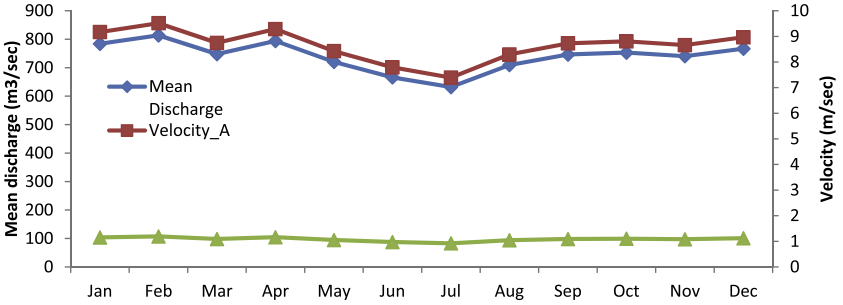


Fig. 10. Turbine Discharge and Estimated Flow Velocities at Kainji HEPS tailrace (m/s).

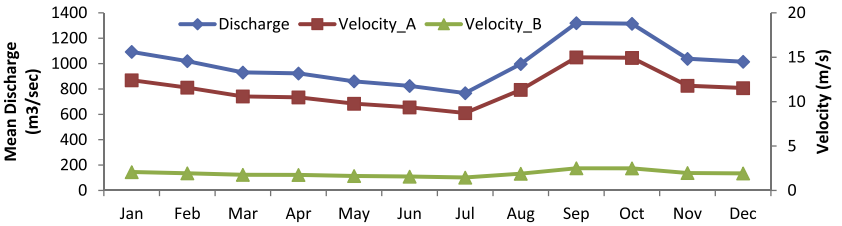


Fig. 11. Turbine Discharge and Estimated Flow Velocities at Jebba HEPS tailrace (m/s).

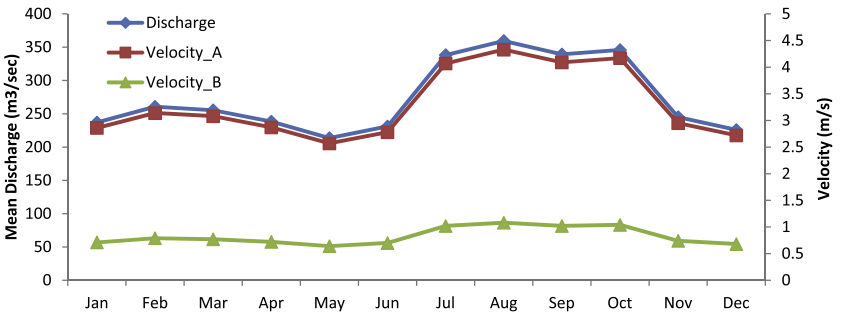


Fig. 12. Turbine Discharge and Estimated Flow Velocities at Shiroro HEPS tailrace (m/s).

2.5. *Power from the hydrokinetic turbines*

The National Centre for Hydropower Research and Development (NACHRED), Energy Commission of Nigeria is developing a hybrid hydrokinetic turbine system that can be used based on the peculiarity of Nigerian hydrology. The turbine is a combination of the lift type vertical axis H-Darrieus turbine, the Squirrel cage Darrieus turbine — a variant of the Darrieus turbine and the Drag type modified Savonius turbine. The turbine is presented in Fig. 13 and some of its specifications in Table 11.

The dimensions and specifications of this hybrid turbine was used for this study to determine the amount of power that can be extracted from a unit. Hydrokinetic power that can be extracted from the Kainji, Jebba and Shiroro HEPS was computed using Eq. (1) based on two statistical methods.

2.5.1. *Hydrokinetic power using time series*

Time series analysis for hydrokinetic extraction involves the use of statistical methods to analyze the time series data of the hydrokinetic resource. Power that can be harvested from the three HEPS was computed using the time series involving the average values of the parameters and for the regions of consideration. The estimated hydrokinetic power that can be harvested in the 3 stations are presented in Tables 12–14 and Figs. 14–16 below.

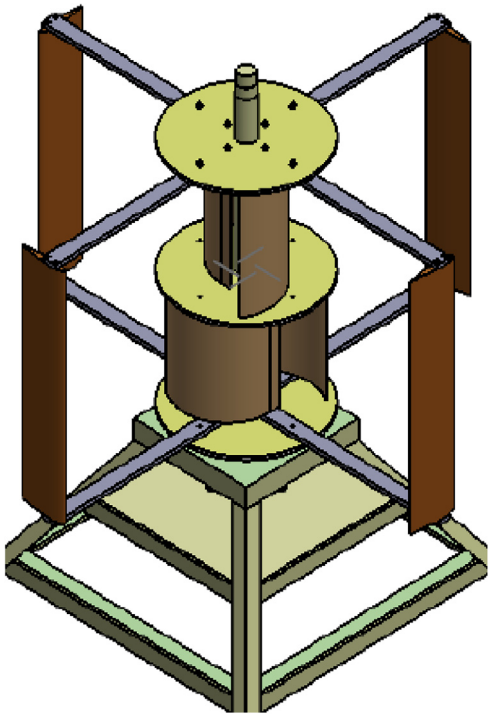


Fig. 13. The hybrid hydrokinetic turbine concept and some of its specifications.

Table 11
Specifications of the hybrid turbine.

S/N	Component part	Dimension
1	Total area of the hybrid turbine	3.055 (m^2)
2	Total blade height of hybrid turbine	1.150 (m)
3	Total turbine diameter	2.040 (m)
4	Darrieus blade chord length	0.233 (m)
5	Darrieus blade thickness	0.035 (m)
6	Darrieus blade height	1.150 (m)
7	Darrieus blade diameter	2.040 (m)
8	Darrieus blade area	2.450 (m^2)
9	Savonius blade diameter	0.550 (m)
10	Savonius blade height	1.100 (m)
11	Savonius blade thickness	0.0016 (m)
12	Savonius blade area	0.605 (m^2)

Table 12
Turbine discharge (m^3/s) and estimated hydrokinetic power in Kainji HEPS.

Month	January	February	March	April	May	June	July	August	September	October	November	December
Mean discharge	784.16	813.77	747.86	793.90	720.41	666.18	632.00	709.35	746.30	752.98	740.50	766.69
HKP_A (MW)	1.176	1.314	1.020	1.221	0.912	0.721	0.616	0.871	1.014	1.041	0.990	1.099
HKP_B (kW)	2.32	2.57	1.97	2.38	1.77	1.39	1.19	1.72	1.97	2.03	1.92	2.14

2.5.2. *Hydrokinetic power estimates from the flow duration curve of turbine discharges*

The flow duration curve (FDC) analysis was carried out for turbine discharges at the 3 hydropower stations. The dependable turbine discharge at 50% exceedence probability was obtained as 760 m^3/s for Kainji, 1000 m^3/s for Jebba and 300 m^3/s for Shiroro. Turbine discharge of other probabilities of exceedence can be obtained from Figs. 17 and 18.

Table 13
Turbine discharge (m^3/s) and estimated hydrokinetic power in Jebba HEPS.

Month	January	February	March	April	May	June	July	August	September	October	November	December
Mean discharge	1092.4	1019.7	930.00	922.54	860.04	824.1	767.27	997.15	1319.2	1314.3	1037.7	1014.57
HKP_A (MW)	2.9	2.4	1.8	1.8	1.4	1.3	1.0	2.2	5.1	5.1	2.5	2.3
HKP_B (kW)	13.5	11.0	8.3	8.2	6.6	5.8	4.6	10.3	23.8	23.5	11.7	10.8

Table 14
Turbine discharge (m^3/s) and estimated hydrokinetic power in Shiroro HEPS.

Month	January	February	March	April	May	June	July	August	September	October	November	December
Mean discharge	236.99	260.65	255.32	238.34	213.58	231.1	338.20	359.43	339.27	345.93	245.03	225.88
HKP_A (kW)	35.5	47.2	44.4	36.1	26.0	32.9	103.2	123.8	104.1	110.4	39.2	30.7
HKP_B (kW)	0.555	0.738	0.694	0.564	0.406	0.514	1.60	1.90	1.60	1.70	0.613	0.480

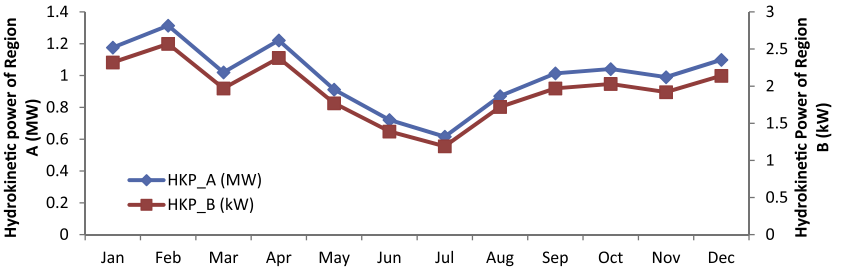


Fig. 14. Estimated hydrokinetic power of regions of interest in Kanji HEPS.

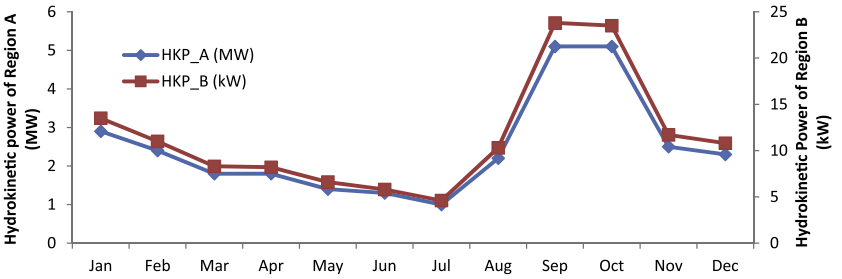


Fig. 15. Estimated hydrokinetic power of regions of interest in Jebba HEPS.

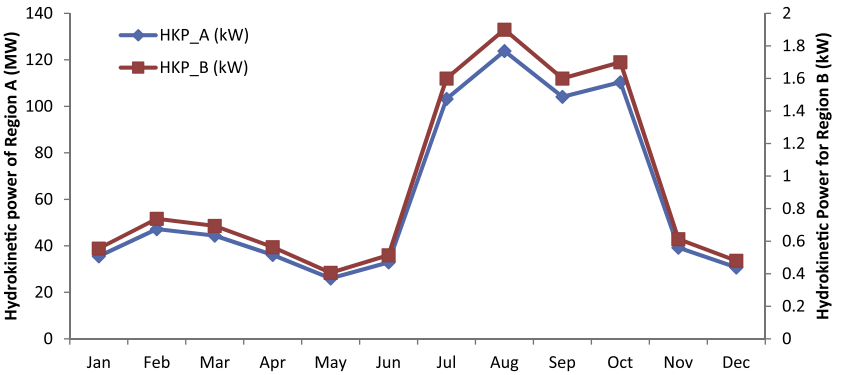


Fig. 16. Estimated hydrokinetic power of regions of interest in Jebba HEPS.

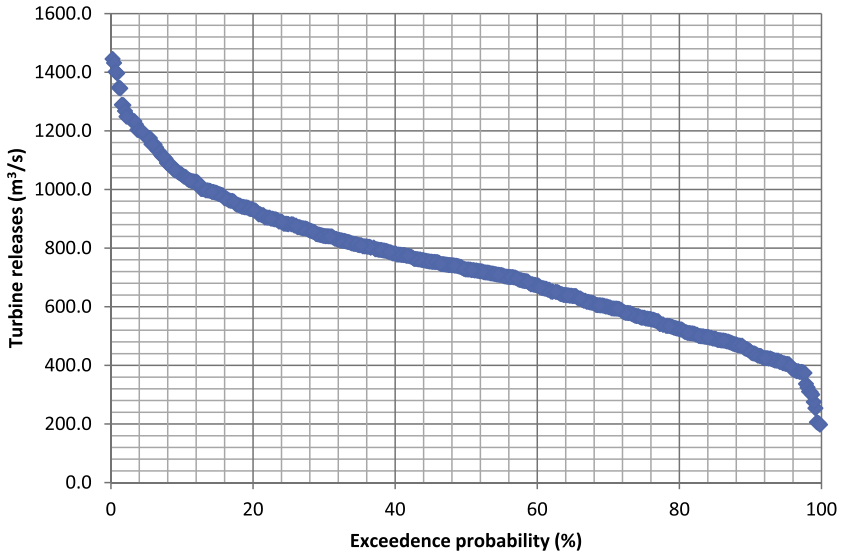


Fig. 17. Flow duration curve for turbine releases at Kainji H.P dam (1970–2009).

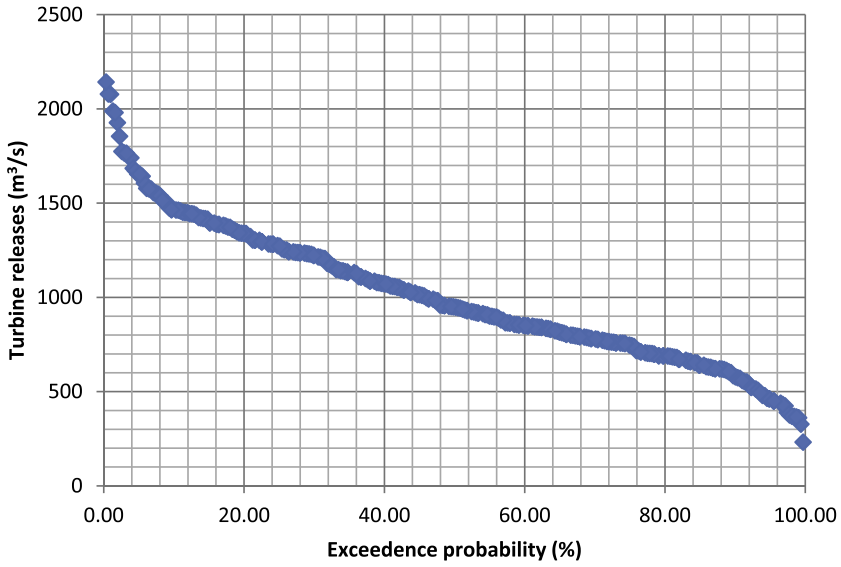


Fig. 18. Flow duration curve for turbine releases at Jebba H.P dam (1984–2009).

The dependable turbine discharges of reliabilities such as 50%, 60%, 75%, 90%, 95% and 99% and the corresponding HEPS energy output and HKP estimates for regions A and B are presented in Tables 15–17. The table shows discharges of various reliabilities that can be guaranteed in the three HEPS. It also presents the hydrokinetic power estimates of different arrays of turbines and the overall energy increase (Fig. 19).

This shows that 760 m^3/s of Turbine Release can be drawn in 50% of the time at Kainji to generate 252 MW of energy from the installed turbines which can be scaled up by the addition of 50 (or more) hydrokinetic turbines to produce 305 MW. This 21% increase over the installed capacity can be achieved with minimal space and minimal effect on existing structures and without any substantial effect on the hydraulic head of the HEPS.

Fig. 20 shows that 1000 m^3/s of Turbine Release can be drawn in 50% of the time at Jebba to generate 230 MW of energy from the installed turbines which can be scaled up by the addition of 50 (or more) hydrokinetic turbines to produce 342.4 MW. This 49% increase over the installed capacity can be achieved with minimal space and minimal

Table 15
Turbine discharge and corresponding hydrokinetic power estimates in Kainji HEPS.

Level of reliabilities (%)	50	60	75	90	95	99
Turbine discharge (m^3/s)	760	720	600	480	440	200
Power output (MW)	252	239	199	159	146	66
Hydrokinetic power (MW) at region (A)	1.071	0.9105	0.527	0.269	0.208	0.0195
Hydrokinetic power (kW) at region (B)	1.694	1.605	1.338	1.070	0.981	0.4458
Total power obtainable for a unit HKT at Kainji HEPS (MW)	253.1	239.9	199.5	159.3	146.2	66.0
Total power obtainable for 10 HKTs at Kainji HEPS (MW)	262.7	248.1	204.3	161.7	148.1	66.2
Total power obtainable for 50 HKTs at Kainji HEPS (MW)	305.5	284.5	225.3	172.5	156.4	67.0
Percentage increase (%)	21.2	19.0	13.2	8.5	7.1	1.5

Table 16
Turbine discharge and corresponding hydrokinetic power estimates in Jebba HEPS.

Level of reliabilities (%)	50	60	75	90	95	99
Turbine discharge (m^3/s)	1000	960	920	540	500	200
Power output (MW)	230	221	212	124	115	46
Hydrokinetic power (MW) at region (A)	2.2	2.0	1.7	0.352	0.279	0.018
Hydrokinetic power (kW) at region (B)	10.4	9.2	8.1	1.6	1.3	0.83
Total power obtainable for a unit HKT at Jebba HEPS (MW)	232.2	223.0	213.8	124.4	115.3	46.0
Total power obtainable for 10 HKTs at Jebba HEPS (MW)	252.5	240.9	229.5	127.5	117.8	46.2
Total power obtainable for 25 HKTs at Jebba HEPS (MW)	286.2	270.7	255.8	132.8	122.0	46.4
Total power obtainable for 50 HKTs at Jebba HEPS (MW)	342.4	320.4	299.5	141.7	129.0	46.9
Percentage increase (%)	48.9	45.0	41.3	14.3	12.2	2.0

Table 17
Turbine discharge and corresponding hydrokinetic power estimates in Shiroro HEPS.

Level of reliabilities (%)	50	60	75	90	95	99
Turbine discharge (m^3/s)	300	280	220	160	120	10
Power output (MW)	228	213	168	122	92	8
Hydrokinetic power (kW) at region (A)	72.0	58.5	28.4	10.9	4.6	2.7
Hydrokinetic power (kW) at region (B)	1.1	0.915	0.444	0.171	0.720	0.417
Total power obtainable for a unit HKT at Shiroro HEPS (MW)	228.1	213.1	168.0	122.0	92.0	8.0
Total power obtainable for 10 HKTs at Shiroro HEPS (MW)	228.7	213.6	168.3	122.1	92.0	8.0
Total power obtainable for 25 HKTs at Shiroro HEPS (MW)	229.8	214.5	168.7	122.3	92.1	8.0
Total power obtainable for 50 HKTs at Shiroro HEPS (MW)	231.7	216.0	169.4	122.6	92.2	8.0
Percentage increase (%)	1.6	1.4	0.9	0.5	0.3	0.0

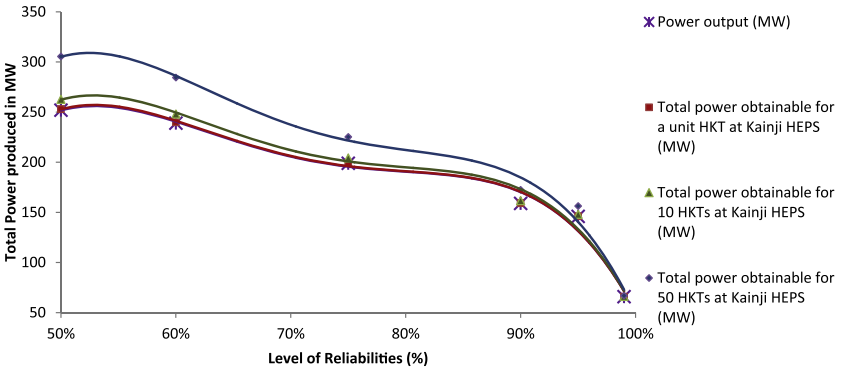


Fig. 19. Chart of obtainable power increase by including hydrokinetic systems in Kainji HEPS.

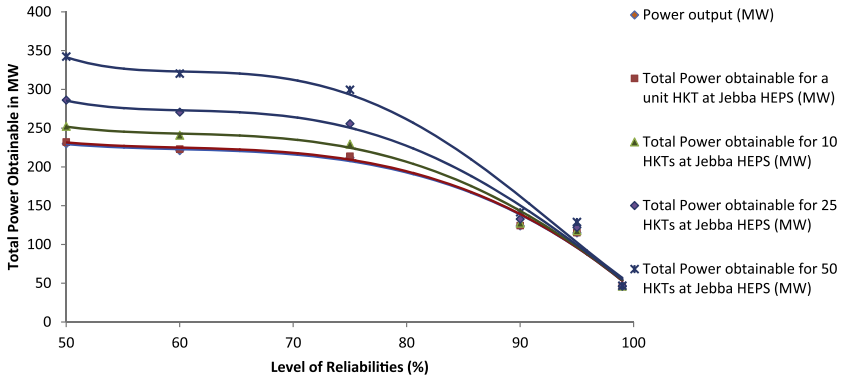


Fig. 20. Chart of obtainable power increase by including hydrokinetic systems in Jebba HEPS.

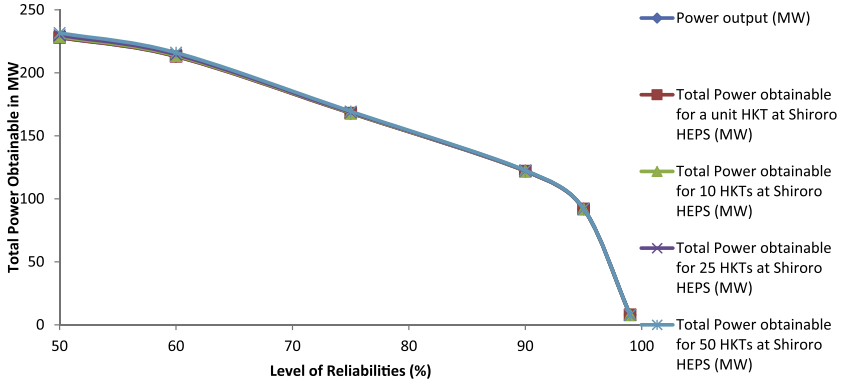


Fig. 21. Chart of obtainable power increase by including hydrokinetic systems in Shiroro HEPS.

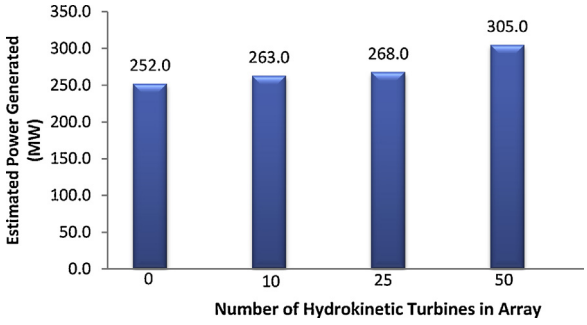


Fig. 22. Estimated power obtainable at Kainji HEPS with Increase in HKT array.

effect on existing structures and without any substantial effect on the hydraulic head of the HEPS. The estimated power generated, with different arrays of turbines, is presented in Fig. 20.

Fig. 21 shows that 300 m^3/s of Turbine Release can be drawn in 50% of the time at Shiroro to generate 228 MW of energy from the installed turbines which can be scaled up by the addition of 50 (or more) hydrokinetic turbines to produce 231 MW. This 1.6% small but not insignificant increase over the installed capacity can be achieved with minimal space and minimal effect on existing structures and without any substantial effect on the hydraulic head of the HEPS. The smaller increase may be due to the low hydrological cycle/hydropower operation time of the station. The estimated power generated, with different arrays of turbines, is presented in Figs. 22–24.

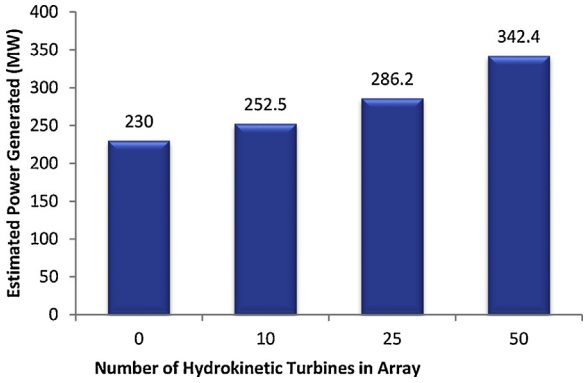


Fig. 23. Estimated power obtainable at Jebba HEPS with increase in HKT array.

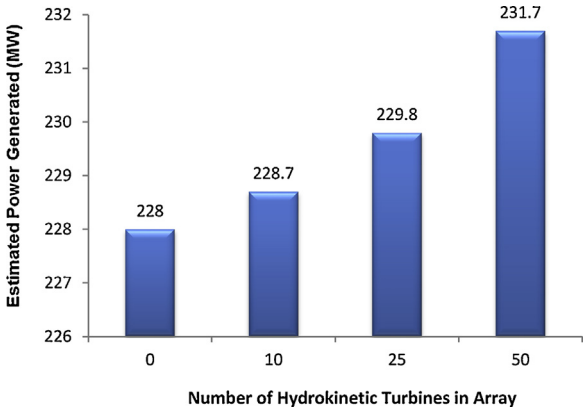


Fig. 24. Estimated power obtainable at Shiroro HEPS with increase in HKT array.

3. Conclusions/future outlook

There is great potential in deploying hydrokinetic turbines at the tail waters of existing hydrodams to extract additional water energy in a technologically and economically feasible way. An array of 10, 25 and 50 turbines (like the NACHRED turbine concept), each with a swept area of 2.45 m^2 can increase the power generation to 263 MW, 268 MW and 305 MW at Kainji HEPS; 252.2 MW, 286.2 MW and 342.4 MW at Jebba HEPS and 228.7 MW, 229.8 MW and 231.7 MW at Shiroro HEPS, Nigeria. Bigger turbine designs with higher swept areas shall produce more hydrokinetic power. Other critical areas for the technological concept to become actualised are the technology and engineering details, man-power availability; the economics; the environmental impacts research, permitting and regulatory issues.

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