Volume 24 (2) 2025 Page 80 - 90

Mekanika: Majalah Ilmiah Mekanika

Hydrodynamic Performance Evaluation of a Double Stage Savonius Turbine on River Ogun, Southwestern Nigeria

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Keywords:
Savonius turbine
River Ogun
Hydrodynamic
Double-stage
Hydrokinetic

Abstract

This study evaluates the hydrodynamic performance of a double-stage Savonius hydrokinetic turbine with a rotor diameter of 0.3m, a rotor height of 0.6m, and a swept area of 0.18 m², designed for deployment in the River Ogun, Southwestern Nigeria. The objective is to assess the turbine's suitability for harnessing energy from low-head rivers. The methodology involved testing the turbine in a riverine environment at selected flow velocities and depths, evaluating its power coefficient (C_p), Tip Speed Ratio (TSR), and power output. The results show that the turbine achieves a maximum C_p of 0.321 at a TSR of 0.5 and a peak power output of 100.9 W at a flow velocity of 1.55 m/s and angular velocity of 5.26 rad/s, and with a cut-in speed of approximately 1.48 m/s. Across all test conditions, the average C_p was approximately 0.3013, indicating an energy conversion efficiency of about 30.1% relative to the total available kinetic power, which is 335.15 W. This result highlights the double-stage Savonius turbine's capacity to extract energy under ultra-low head and low-velocity conditions efficiently and highlights the importance of optimizing turbine design and operating conditions for improved energy generation efficiency.

1 Introduction

The pursuit of renewable energy sources has become globally imperative, driven by the need to mitigate climate change, ensure energy security, and promote sustainable development. Therefore, hydrokinetic energy has emerged as a promising alternative, harnessing the power of moving water to generate electricity. One innovative technology that has shown great potential in this field is the Horizontal Axis Savonius Hydrokinetic Turbine (HASHKT) [1,2]. The Savonius turbine has emerged as a promising solution for capturing energy from low-speed water flows due to its simple design, self-starting ability, and adaptability to various environmental conditions [3]. This type of turbine is particularly suited for deployment in rivers, tidal currents, and ocean currents, where it can capture the kinetic energy of flowing water and convert it into electricity

https://dx.doi.org/10.20961/mekanika.v24i2.104492

Revised 11 August 2025; received in revised version 04 August 2025; Accepted 21 August 2025
Available Online 20 October 2025

2579-3144

The Savonius rotor features a unique "S" shaped blade design that captures the kinetic energy of flowing water, causing the rotor to spin and drive an electrical generator [1,4,5]. Savonius turbines are particularly useful in rural or off-grid regions where access to electricity is limited or non-existent [2,6]. Key advantages of the HASHKT system are its ability to operate in low-head conditions. It is relatively simple in design, with fewer moving parts compared to traditional hydroelectric turbines, which reduces maintenance costs and increases reliability. Their capacity for local fabrication further enhances their appropriateness for deployment in developing countries [3,7]. Additionally, the HASHKT system can be designed to operate in both directions of flow, making it suitable for deployment in tidal currents and other environments with reversing flow [8]. They can have multiple blades, and they can also be set in multiple stages. Figure 1 presents a Savonius turbine with varying numbers of blades. Figure 2 presents schematic and plate figures of Savonius turbines with different stages.

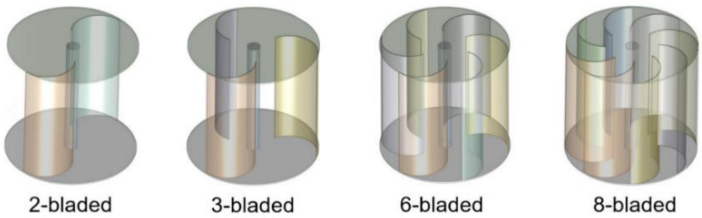


Figure 1. Savonius turbines with different blade numbers [9]

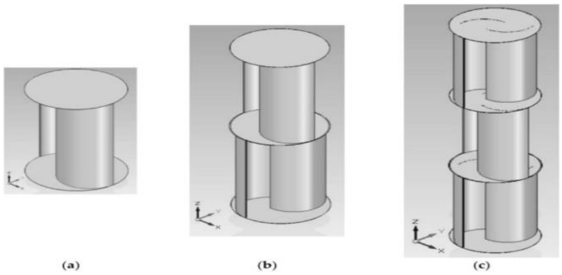


Figure 2. Schematic diagram of vertical axis: (a) Single stage Savonius turbine, (b) 2-Stage Savonius turbine, and (c) 3-Stage Savonius turbine [10]

The performance of HASHKT systems is influenced by several interrelated factors, including rotor design, turbine diameter, and flow velocity [4,11]. Research has demonstrated that careful optimization of these parameters can significantly enhance both the efficiency and power output of the system [12,13,14]. Several studies have shown that double-stage Savonius configurations, as shown in Figure 3, significantly enhance power output and torque performance, especially when rotor blades are offset by 90°, as this setup maximizes power coefficient at optimal TSRs [3,15,16,17]. Experimental investigations have further indicated that varying the inter-stage gap in two-stage Savonius turbines can impact hydrodynamic performance, with optimal spacing leading to improved power generation under ultra-low flow conditions typical of riverine systems [17].

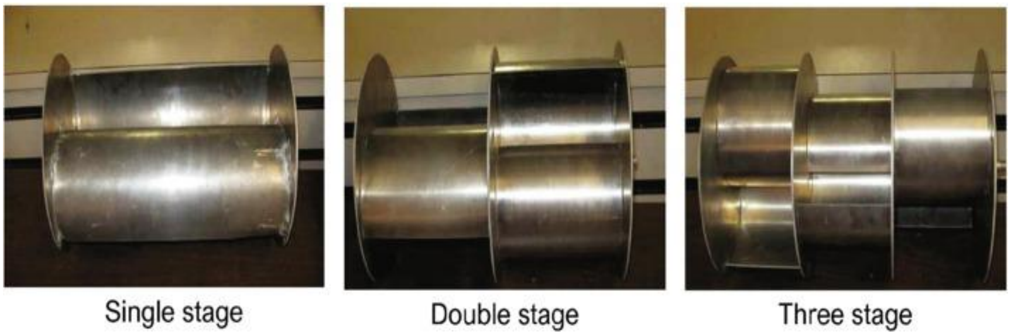


Figure 3. Plate of horizontal axis: (a) Single stage Savonius turbine, (b) 2-Stage Savonius turbine (c), and 3-Stage Savonius turbine [12]

The double-stage arrangement not only improves power efficiency but also reduces self-starting speeds and torque fluctuations, making it particularly suitable for narrow and shallow rivers in rural settings [18]. Computational studies have corroborated these findings, demonstrating that a two-blade, double-stage configuration yields superior torque and power output compared to three- or four-blade models, with the highest efficiency observed at a TSR of 0.6 [19]. Moreover, the integration of deflectors and optimization of geometric parameters, such as blade twist and height-to-diameter ratio, can significantly enhance the turbine's power coefficient, with values reaching up to 0.51 under well-tuned conditions [20]. These insights are crucial for the deployment of small-scale hydrokinetic systems in sub-Saharan Africa, such as along the River Ogun, where flow velocities are modest yet consistently available.

To contribute to this field, the current study focuses on the development and hydrodynamic performance evaluation of a Double-Stage Savonius Hydrokinetic Turbine (DSSHKT) specifically designed for deployment in River Ogun, Southwestern Nigeria. This region presents ideal conditions for field-based performance assessments, given its moderate but consistent flow velocities and accessibility for system monitoring. The double-stage configuration is selected based on evidence suggesting its superior performance over single-stage models, particularly under ultra-low flow conditions. In this turbine architecture, blades on each stage are offset by 90°, a configuration proven to reduce torque fluctuations and enhance self-starting capabilities. Additionally, such designs facilitate better energy capture by extending the interaction time between the rotor and flowing water. By incorporating site-specific parameters into the design, the study seeks to assess the operational feasibility and performance viability of DSSHKT under realistic rural Nigerian river conditions. The outcomes are expected to inform future applications of hydrokinetic technologies in similar environments.

2 Experimental Methods

2.1 Study area: Odo-Ogun site along River Ogun, Southwestern Nigeria

Odo-ogun is a rural settlement located along the Oyo-Iseyin Road in the Southwestern state of Oyo, Nigeria, as shown in Figure 4. It is situated near the River Ogun, downstream of the Ikerre Gorge dam. It lies between coordinates 875232.89 N, 578464.09 E and 871820.67 N, 576912.95 E. The settlement is characterized by a sparse population, with residents primarily engaged in agricultural activities, which take advantage of the fertile soil and abundant water supply from the river. Rolling hills, wooded areas, and extensive farmland characterize the landscape surrounding Odo-ogun.

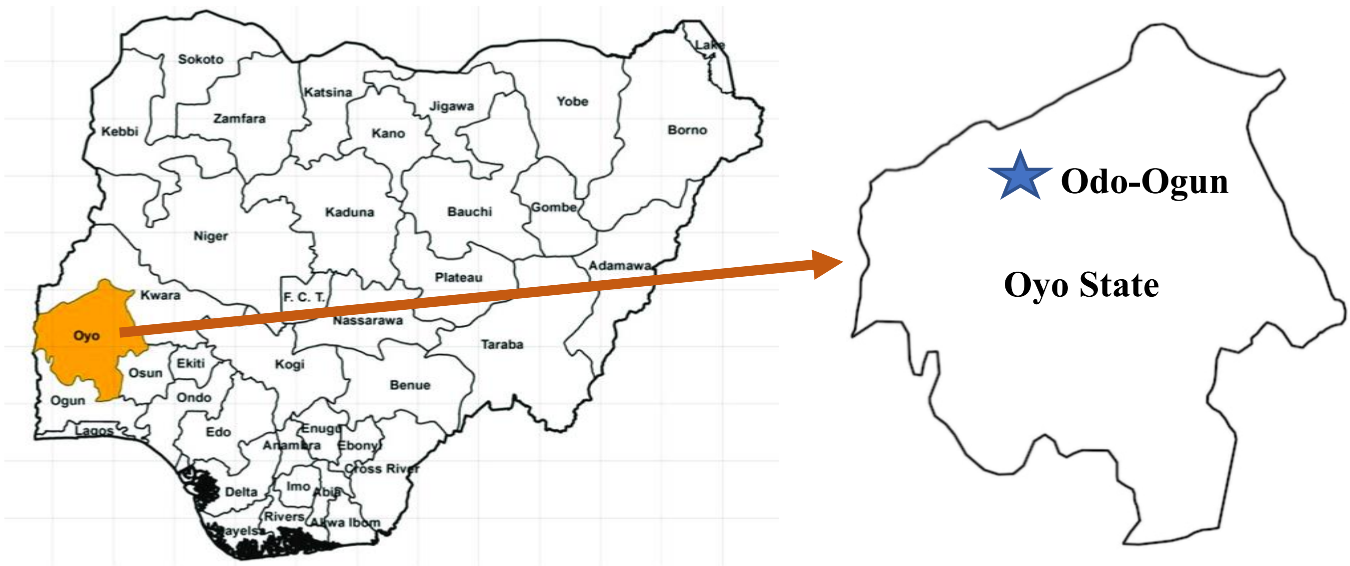


Figure 4. Odo-ogun is located along the Oyo-Iseyin Road, Oyo State, Southwestern Nigeria, and is downstream of the Ikerre Gorge dam

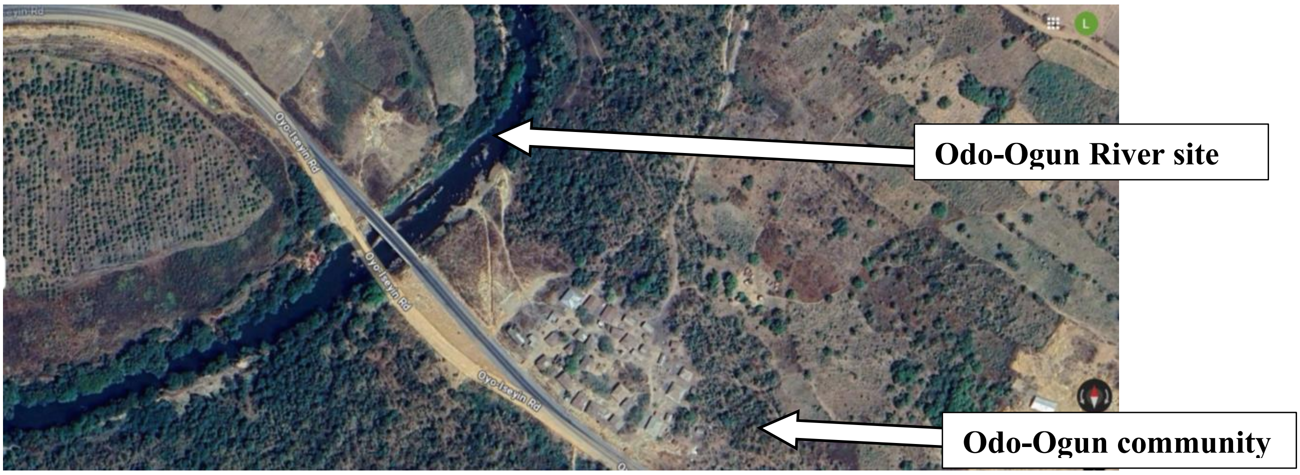


Figure 5. Skyview of the Odo-ogun community and river site

The River Ogun, which flows through the settlement, as shown in Figure 5, is a significant watercourse in the region, providing irrigation for crops, drinking water for humans and livestock, and supporting a diverse range of aquatic life. At the test site, the river is characterized by a moderate flow rate, with a width of approximately 50 meters and a depth of up to 3 meters during the wet season. The riverbank is lined with vegetation, including trees, shrubs, and grasses, which help to stabilize the soil and prevent erosion.

2.2 Design of the double-stage Savonius hydrokinetic turbine system

The double-stage Savonius turbine is a type of Vertical-Axis Wind Turbine (VAWT) that consists of two stages of Savonius turbines stacked on top of each other. Each stage has a rotor diameter of D and a rotor height of H. The turbines are designed to capture wind energy from any direction, making them suitable for installation in urban and complex terrain areas. The double-stage design allows for a higher power coefficient and increased energy capture compared to a single-stage Savonius turbine. The rotor blades of the double-stage Savonius turbine are cup-shaped and are arranged in a staggered configuration to maximize energy capture. The rotor blades are designed to rotate at a slow speed, typically between 50 and 100 rpm, which reduces noise and vibration.

The aspect ratio (AR) of the rotor blades is defined as the ratio of the blade height to the blade chord length (see Equation 1).

$$AR = \frac{H_{blade}}{c} \tag{1}$$

where H_{blade} is the blade height and c is the blade chord length [16]. The blade arc angle (θ) is defined as the angle between the blade and the vertical axis (see Equation 2).

$$\theta = arcsin\left(\frac{D/_2}{H_{blade}/_2}\right) \tag{2}$$

The rotor solidity (σ) is defined as the ratio of the total blade area to the rotor swept area (see Equation 3).

$$\sigma = \left(\frac{N_{blades}A_{blade}}{A}\right) \tag{3}$$

where N_{blades} is the number of blades, A_{blade} is the blade area, and A is the rotor swept area [14]. The structural members of the turbine, including the shaft, bearings, and foundation, were designed to withstand the stresses and loads imposed by the turbine's operation. The shaft diameter (d) can be calculated using Equation 4.

$$d_{shaft} = \left(\frac{32n_s}{\pi\sigma_y}\sqrt{(M^2 + T^2)}\right)^{\frac{1}{3}} \tag{4}$$

where (n_s) is the factor of safety, σ_y is the yield strength of the material. M and T are the static moment and dynamic torque, respectively, acting on the shaft [21]. The bearing selection and design took into account the radial and axial loads imposed by the turbine's operation. The bearing life (L) can be calculated using Equation 5.

$$L_{bearing} = \left(\frac{C}{P}\right)^p \tag{5}$$

where C is the bearing capacity, P is the load, and p is the load-life exponent. Gross theoretical hydrokinetic power resource (P_{th}) is the segment-specific gross naturally available hydrokinetic resource. The gross and recoverable hydrokinetic power available was estimated using Equations 6 and 7.

$$P_{th} = \gamma Q \Delta H \tag{6}$$

where: P_{th} is theoretically available hydrokinetic power (watts), Q is the discharge (m^3/s), ΔH is hydraulic head (m), γ is the specific weight of water (N/m^3) [6].

The recoverable power output (P) of a DSSHKT can be determined using Equation 7.

$$P = \frac{1}{2}\rho A V^3 C_p \tag{7}$$

where ρ is the water density, A is the turbine's swept area, V is the flow velocity, and C_p is the power coefficient. The turbine's rotational speed (ω) can be calculated using Equation 8.

$$\omega = \left(\frac{\pi N}{60}\right) \tag{8}$$

where N is the rotational speed in rpm. The power coefficient (C_p) of the double-stage Savonius turbine is a measure of its efficiency in capturing wind energy. The C_p value can be calculated using Equation 9.

$$C_p = \frac{(P\omega)}{0.5\rho A v^3} \tag{9}$$

where P is the power output, ρ is the air density, A is the rotor swept area, and V is the wind speed. Maximum torque on a turbine rotor occurs when maximum thrust can be applied at the blade tip farthest from the axis. Equations 1-13 show the relationships of maximum torque, maximum thrust on the turbine, and velocity of flow. Table 1 shows a summary of the design.

$$T_{max} = f_{max} \times R \tag{10}$$

$$f_{max} = \frac{1}{2}\rho A V^2 \tag{11}$$

$$T_{max} = \frac{1}{2}\rho A V^2 R \tag{12}$$

$$T = C_t T_{max} \tag{13}$$

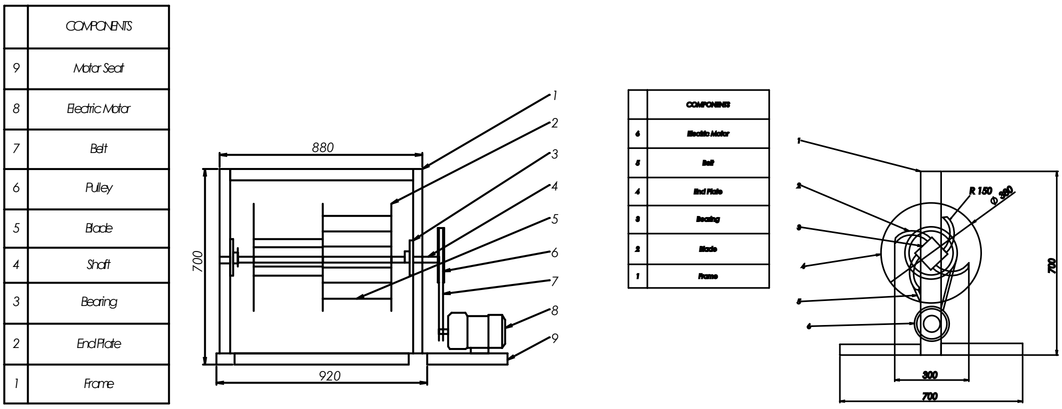
where: ρ is density of water (kg/m^3); A_s is swept area of rotor (m^2); V is velocity of water flow (m/s); R is blade radius (m); C_t is coefficient of thrust (dimensionless); f_{max} is maximum thrust on turbine (N); T_{max} is maximum torque on rotor (Nm); T is torque on rotor (Nm)

Table 1. Design parameters of the test Savonius turbine

Parameter	Value
rotor diameter (D_{sav})	0.3 m
rotor height	0.6 m
swept area (A_s)	0.18 m^2
diameter of end plates (D_o)	0.38 m
stage height (h)	0.3 m
stage aspect ratio (AR_{stage})	0.99
thrust on shaft (T_{shaft})	260.1 N
drag force on shaft (M)	104 N
hydrokinetic power ($P_{hydrokinetic}$)	100.9 W
torque transmitted by the shaft	19.2 Nm
diameter of shaft	0.02 m
overlap ratio	0.2
shaft speed (rpm)	216.55 rpm
Tip Speed Ratio (TSR)	2
blade arc angle	124˚

2.3 Fabrication of the turbine

Materials for the fabrication of the developed Savonius turbine were selected based on considerations of the desired physical and mechanical properties of various members of the developed turbine. Materials were sourced locally for the fabrication. Fabrication was carried out at the Mechanical Metal Workshop of the Lower Niger River Basin Development Authority, Ilorin. The developed Savonius turbine was tested on the Middle Ogun irrigation river. Orthographic views of the turbine, exploded view, and isometric views were shown in Figures 6 and 7, respectively.



(a) (b)

Figure 6. Orthographic diagram with front and side views of the turbine

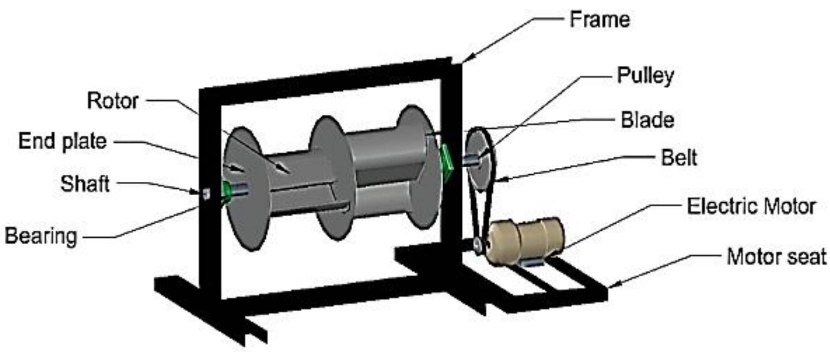


Figure 7. Isomeric view of the Savonius turbine

2.4 Experimental setup and performance testing

During testing of the Savonius hydrokinetic turbine system, the fabricated turbine was deployed at the peak of the rainy season in the laminar zone of the controlled riverine laboratory. The predetermined depths of measurement were set, and the water flow velocity was monitored to be relatively steady. The turbine rotor was then gently lowered into the waters. The rotor revolutions were allowed to reach a steady state/high value after the water flow had reached its constant speed. Measuring instruments were then introduced to harvest some essential parameters, as shown in Figure 8.

(a) (b) (c)

Figure 8. (a) Experimental test activities in River Ogun, (b) Guaging activities in the river, and (c) The double-stage Savonius test turbine

The torque and power output of the turbine were evaluated using the rope brake dynamometer. The dynamometer applies a load to the turbine's rotating shaft, and the resulting torque and rotational speed are measured to calculate the turbine's performance characteristics. The rotational speed was measured using the tachometer, an instrument that detects the rotation of the turbine shaft, and displays the estimated speed in Revolutions Per Minute (RPM). A water current meter was used to measure the speed and direction of the river flow.

3 Results and Discussion

Table 2 presents the results of the performance evaluation of the Savonius double-stage turbine at varying water velocities ranging from 1.48 to 1.58 m/s. The flow velocities at different points (v_{water}) as well as the corresponding shaft speed, thrust, and torque were measured and used to compute the expected power and the actual power delivered. Rotor diameter was 0.3 m while the rotor swept area was 0.18 m^2. As water velocity increases, both the shaft speed and angular velocity also increase slightly, indicating a consistent response from the turbine. The expected power output is higher than the actual power (calculated as torque × angular velocity), due to system losses and inefficiencies. The TSR remains around 0.5, showing that the turbine is operating in a relatively stable and efficient range. The power coefficient (C_p) varies from 0.28 to 0.32, suggesting the turbine captures approximately 28-32% of the available kinetic energy from the flow.

The C_p-TSR curve, as shown in Figure 9, for the Savonius turbine exhibits an arc-shaped relationship, characteristic of this turbine type. The curve begins at a C_p of 0.15 and TSR of 0.45, increases to a maximum C_p of 0.32 at TSR 0.5, and then decreases to C_p 0.28 at TSR 0.525. This trend suggests that the turbine's efficiency improves as the TSR increases up to the optimal point (TSR = 0.5), beyond which efficiency decreases.

Table 2. Experimental and computational results of the Savonius turbine testing

V_{water} (m/s)	Shaft Speed (rpm)	Ang. Vel. (rad/sec)	Power (W) (Expected)	Thrust (N)	Torque (Nm)	Power ($T\times\omega$) (Actual) (W)	TSR	C_p
1.48	47.37	4.960571	291.7613	126	18.9	93.75478	0.502761	0.321341
1.5	47	4.921824	303.75	128	19.2	94.49903	0.492182	0.311108
1.58	48.2	5.047488	354.9881	131	19.65	99.18314	0.479192	0.279399
1.55	49.2	5.152208	335.1488	130	19.5	100.468	0.498601	0.299772
1.55	50.2	5.256927	335.1488	128	19.2	100.933	0.508735	0.301159
1.54	49	5.131264	328.7038	127	19.05	97.75057	0.499798	0.297382

The C_p-TSR curve, as shown in Figure 9, for the Savonius turbine exhibits an arc-shaped relationship, characteristic of this turbine type. The curve begins at a C_p of 0.15 and TSR of 0.45, increases to a maximum C_p of 0.32 at TSR 0.5, and then decreases to C_p 0.28 at TSR 0.525. This trend suggests that the turbine's efficiency improves as the TSR increases up to the optimal point (TSR = 0.5), beyond which efficiency decreases. This is likely due to the balance between the turbine's ability to capture energy from the flow and the increasing losses associated with higher TSR values, such as blade drag and flow separation. The results imply that the turbine design is optimized for operation at a TSR of around 0.5, where it achieves maximum efficiency. Operating the turbine at higher or lower TSR values may result in reduced efficiency.

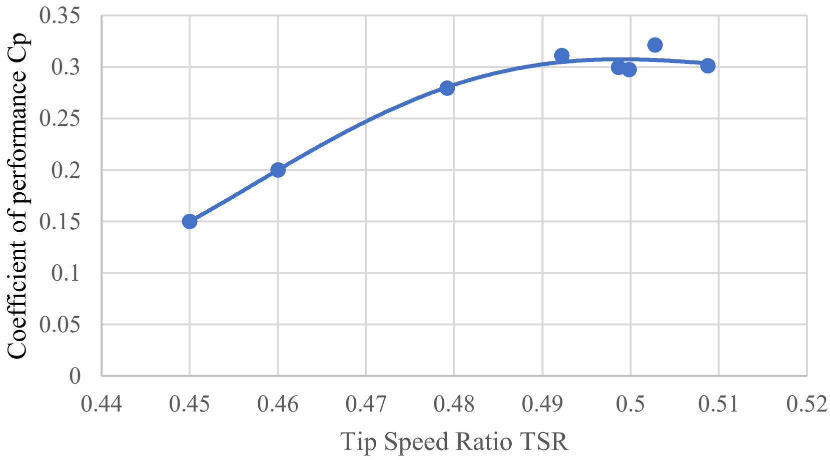


Figure 9. C_P-TSR curve for the double-stage Savonius turbine

The double-stage design of the Savonius turbine played a significant role in the observed results, as it enabled more efficient energy extraction from the flow. The second stage captures energy from the flow that the first stage does not, resulting in higher efficiency and power output. Compared to other studies in the literature, the maximum C_p value of 0.32 obtained in this study is comparatively higher. Typical C_p values for Savonius turbines range from 0.15 to 0.25. The double-stage design may be responsible for this improved performance.

However, it's essential to note that C_p values can vary widely depending on the specific turbine design, operating conditions, and testing setup. A study by Kamoji et al. [22] reported a maximum C_p of 0.21 for a single-stage Savonius turbine. Another survey by Nimvari et al. [23] achieved a maximum C_p of 0.274 for a Savonius turbine with a porous deflector. In comparison, the current study's optimal C_p of 0.32 indicates that the double-stage design and optimization of the turbine's parameters have resulted in improved performance.

The rotational speed-flow velocity curve, as shown in Figure 10, of the Savonius turbine exhibits a unique profile, starting from a rotational speed of 4.95 rad/s at a flow velocity of 1.48 m/s. As the flow velocity increases to 1.5 m/s, the rotational speed decreases slightly to 4.92 rad/s, marking an inflection point where the curve changes direction.

Beyond this point, the rotational speed increases with the flow velocity, reaching a maximum of 5.25 rad/s at a flow velocity of 1.55 m/s. However, the curve then decreases, with the rotational speed dropping to 5.13 rad/s at a flow velocity of 1.54 m/s. This curve suggests that the flow velocity influences the turbine's efficiency, and the inflection point may indicate the optimal operating point for the turbine. The decrease in rotational speed at higher flow velocities may indicate design limitations, such as blade stall or flow separation, which reduce the turbine's efficiency. Further investigation is needed to optimize the turbine's design and operating conditions.

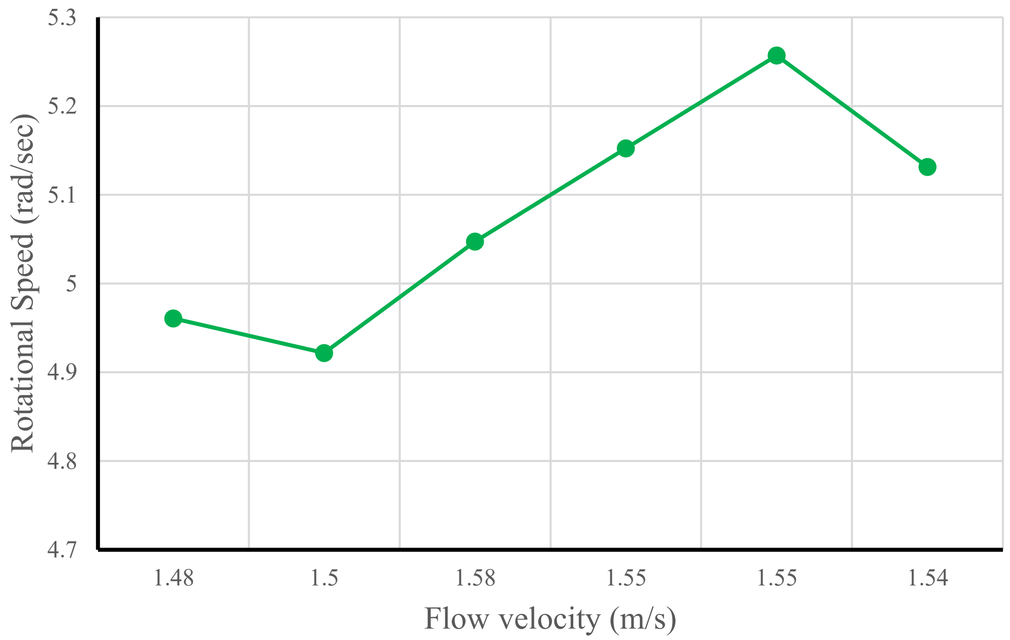


Figure 10. Rotational shaft speed-water flow velocity curve for the double-stage Savonius turbine

Figure 11 shows the power curve, indicating the power output as a function of the streamflow velocity using the developed Savonius turbine. The power curve exhibits an exponential trend, consistent with the theoretical expectations for hydrokinetic turbines. The curve begins at a flow velocity of 1.48 m/s, corresponding to a power output of 94 W. As the flow velocity increases to 1.51 m/s, the power output marginally increases to 95 W. The power output then rises more sharply, peaking at 100.5 W when the flow velocity reaches 1.55 m/s. The cut-in speed is approximately 1.48 m/s. This value is relatively low, indicating that the turbine can effectively harness energy from slow-moving water currents. The average streamflow speed can be inferred to be approximately 1.5-1.6 m/s, based on the range of flow velocities tested. This average speed is suitable for operating the two-stage Savonius hydrokinetic turbine.

The rated speed, corresponding to the maximum power output, appears to be approximately 1.55 m/s, at which the power output peaks at 100.5 W. This suggests that the turbine is optimized for operation within this flow velocity range, making it suitable for low-head applications, such as riverine or canal-based hydrokinetic energy harvesting. The peak power output of 100.5 W indicates that multiple turbines can be deployed to generate significant amounts of energy, particularly in rivers with consistent flow rates. The exponential power curve trend suggests that optimizing turbine design for specific flow velocity ranges can lead to improved energy generation efficiency.

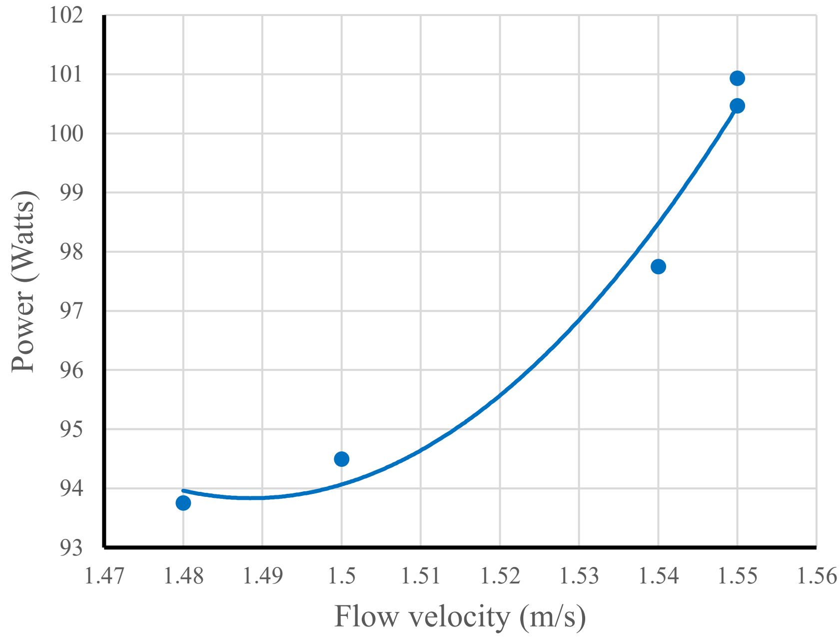


Figure 11. The Savonius hydrokinetic power curve

4 Conclusions

This study has demonstrated the hydrodynamic performance of DSSHKT designed for deployment in River Ogun, Southwestern Nigeria. The results show that the turbine achieves a maximum power coefficient (C_p) of 0.32 at a TSR of 0.5, indicating optimal efficiency at this operating point. The double-stage design of the turbine likely contributes to its improved performance, allowing for more efficient energy extraction from the flow. The power curve analysis reveals that the turbine can effectively harness energy from slow-moving water currents, with a cut-in speed of approximately 1.48 m/s. The peak power output of 100.5 W at a flow velocity of 1.55 m/s suggests that the turbine is suitable for low-head applications, such as riverine or canal-based hydrokinetic energy harvesting. The findings of this study contribute to the growing body of research on hydrokinetic energy in Nigeria, providing valuable insights into the feasibility of using Savonius hydrokinetic turbines for energy generation in riverine environments. Overall, this study highlights the importance of optimizing turbine design and operating conditions to improve energy generation efficiency. Further research and development are necessary to refine the design of the double-stage Savonius turbine and explore its deployment in various riverine environments. The insights gained from this study can inform the development of hydrokinetic energy projects in Nigeria and other regions with similar riverine characteristics.

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