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# Application of low-cost hydrokinetic technology for accelerating electricity access to rural areas in developing economies: field experiment in Kenya

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## Abstract

This article presents the design, construction and field test of an experimental prototype of a low-cost hydrokinetic turbine technology made of local materials and e-waste components. The aim of this study is to investigate the performance of the turbine when subjected to field conditions in low flow velocity rivers. The research and development (R&D) involve the use of e-waste boat motor and locally available materials to develop a modular hydrokinetic turbine for generation of electricity using kinetic energy of rivers. A decommissioned boat motor with a 0.24 m diameter rotor is operated as a turbine. A shroud for flow acceleration was developed from 1.5 mm thick stainless-steel plates and a support structure constructed using angle lines. The field test results of the prototype generated about 11.543 ± 0.021 W and 37.129 ± 0.021 W or (equivalent of 0.011543 kWh and 0.037129 kWh) when operated at an approach flow velocity of 0.8 m $s^{-1}$ and 1.2 m $s^{-1}$ respectively. The wire to water ratio was determined instead of the $C_p$ and the turbine achieved an overall wire to water efficiency of 0.99 and 0.95 respectively. This prototype technology can sustainably provide 24 h energy, sufficient to charge batteries in the rural areas and also provide opportunities within the community such as mobile charging points. An upscaled version of this low-cost technology can be adaptable in rural off-grid communities to enhance the access to electricity in developing countries.

## 1. Introduction

Energy is an important component required for the economic growth and progress of the country. Its availability, accessibility and reliability make it possible for a country to improve the quality of life which promotes the human prosperity through enhanced production of goods and provision of the essential services [1, 2]. Significant amount of the world's energy supply rely on fossil fuels (≈85%) and these sources contains substantial amount of anthropogenic greenhouse gases (GHG) proportionately 56% that have negative effects on the environment and acceleration of the climate change crisis [2, 3].

Kenya's rural population rely mostly on the use of diesel-powered generators for the power generation as the cheapest available option to offer basic services like charging phones or batteries, running the businesses and lighting [4]. Most homesteads utilize the paraffin lamps for their home lighting, with major energy source of cooking derived from wood fuel [2], which also have detrimental effects such as chronic respiratory health complications [5]. The ongoing increase in price of petroleum products and need to fetch the much-needed diesel from the urban areas situated miles away from the rural areas adds to the high overall cost of the commodity and this makes it unsustainable. The generators produce loud noises and also require regular maintenance [6]. In addition, the continuous use of fossil fuels results to the accelerated environmental degradation influencing the global warming effects [7].

Kenya's energy demand grows progressively as the population growth increase but this has been met by the inadequate investment in the power production sector. There is generally an over-reliance on hydropower sources as the chief renewable energy which is greatly affected by the temporal and spatial fluctuation of rainfall in the country. Kenya's large hydropower resources has estimated potential of 3000–6000 MW with the underdeveloped economic potential estimated at 1509 MW of which 1310 MW found to be suitable for 30 MW projects or bigger [8, 9]. The small, mini and micro hydropower potential is estimated at 3000 MW countrywide within approximately 55 rivers which are mainly found within the rural areas where stand-alone systems are suitable for off-grid communities power supply [2].

The electricity demand in rural areas have low load factor making grid connection in rural areas economically unfeasible [10]. The renewable energy technology has considerably offered an alternative low-cost options for rural electrification through the development and implementation of stand-alone options in areas with large distances, small population and low energy demand worldwide [11]. Wind and solar photovoltaics have been intensively developed as stand-alone options and have effectively served the off-grid rural communities worldwide [12], with considerable rural population in Kenya served with solar photovoltaics [8]. However, wind or solar energy are not reliable in regions with still wind flow or overcast weather that hinders the effectiveness of wind turbines and solar photovoltaic cells respectively [6, 13].

Remote rural areas such as in Kenya which are located within the proximity to rivers can effectively make use of the pico-hydrokinetic turbine systems (HKT) for rural electrification [1, 14]. The hydrokinetic river technology has proved effective in providing an alternatively economical and reliable electricity option for the most isolated regions with no grid connections [15]. As a result, the off-grid areas can be significantly compensated for the non-continuous availability of related small scale renewable energy technologies like solar photovoltaics and wind turbines [7]. The HKT is more attractive due to its predictability compared to wind and solar that depends on the daily weather conditions (wind and solar availability). The HKT has some advantage for adoption in remote rural areas as it can operate 24/7 as long as there is flow in the streams/rivers compared to solar-PV and wind energy that requires sun energy and wind flow respectively. The technology can also be attributed to cause minimal environmental impact since minimal to no civil engineering works are required in comparison to the conventional hydropower plants [16, 17]. HKT operate as a run-of-river power plant that is compact and modular in nature which allows its usage to be transferred from one place to another when necessary.

Like many other isolated and sparsely distributed rural homes in off-grid schemes, poor families such as in Kenya rely on cheaper options such as use of dry cell batteries on hand-held torches and radios. For those with a bit of financial capability afforded the rechargeable automotive batteries which could supply higher power consumption loads like fluorescent lamps and small televisions [18]. Upon depletion the battery needs to be transported to a nearby trading centers which could be several kilometers away to be recharged with either grid-connected electricity or diesel generator power and costing between US $ 1.00 and associated inconveniences [18]. The solar PV use has exponentially grown in Kenya for instance with an estimated annual cumulative sale exceeded 100,000 units by the year 2000. The trend has further grown in the current period with approximately 20,000 units sales per year. Still the Solar-PV installed cost per household is estimated between US $ 200–350 depending on the type as either amorphous silicon or crystalline with the latter being the most expensive. The performance depends on the solar availability and requires the use of battery for energy storage for use at nights. The energy availability in upland areas in Kenya is not guaranteed for instance as these areas can experience 3 or more months almost cloudy weather but are having abundant rainfalls with continuous flowing rivers. Even though the cost of solar power is expected to fall with the competition in the market and advancement in technology that lowers the production cost, hydrokinetic turbines will ensure continuous power supply without the need for energy storage batteries, provide AC power and operate at all weather conditions.

Hydrokinetic technology utilizes the kinetic energy of flowing water unlike the conventional potential head of falling water to generate electricity [6, 7, 19, 20]. The technology utilizes similar physical principles with wind turbine systems in operation, electrical hardware and variable speed capability for optimal energy extraction [21]. Since water is denser than air almost 800 times (density of water $= 1000$ kg m$^{-3}$, density of air $=$ 1.2 kg m$^{-3}$) the application of HKT therefore has an advantage on the capability of energy extraction even at low speed compared to wind turbines operating under similar conditions [7, 22, 23]. Rated wind speed that wind turbines are designed for lies between 11–13 m s$^{-1}$, while the river turbines with flow acceleration devices can effectively operate under water velocities of 1.17–1.38 m s$^{-1}$ or more depending on the site resources. This is an indication of possible higher energy generation via a river turbine when compared to an equally sized wind energy converter [24]. The theoretical power generated by the HKT system is determined in a similar manner as that of wind turbine system using the equation 1.1below:

$$P = 0.5A\rho v^3 \tag{1.1}$$

**Table 1.** Prices and characteristics of selected commercial HKT. Adapted from [25], Copyright (2020), with permission from Elsevier.

| Company | Rated power, kW | Flow velocity m/s for rated power | Power at 1 m $s^{-1}$ | Turbine diameter (m) | Price, USD ($) |
|---|---|---|---|---|---|
| New energy corp | 5.0 | 3.0 | 0.185 | 1.5 | 50,000 |
| Smart hydro | 5.0 | 3.1 | 0.168 | 1.0 | 14,000 |
| Idénergie | 0.5 | 3.0 | 0.018 | — | 9,875 |
| Green-energy hydrocat | 0.183 | 1.0 | 0.183 | — | 16,600 |
| Waterrotor | 1.0 | 1.8 | 0.171 | — | 5,000 |
| EcoCinetic | 2.0 | 3.0 | 0.074 | — | 4,900 |
| Ibasei cappa | 0.25 | 2.0 | 0.031 | — | 12,000 |

where A is the swept area of the rotor ($m^2$), ρ represents the density of water (1000 kg $m^{-3}$), v is the current velocity of the river (m/s).

Worldwide several developing countries have adopted the application of pico and micro-hydrokinetic turbines and proved that the system is indeed of significance in enhancing energy access to underserved rural areas e.g., in Kenya and Nepal [18].With the numerous potential sites in the rural equatorial regions, the utilization of hydrokinetic turbine systems as the technology is expected to be effective since HKT only requires free-flowing streams with adequate flow speed and depths [25].

Several research and developments have been done to improve the performance of the HKT systems with consideration of design optimization, turbine placement, augmentation and techno-economic feasibility [26, 27]. The available HKTs in the market have been optimized for large flows and high tidal currents and are therefore too expensive to be afforded by the people who mostly need them in the developing countries as depicted in table 1 below [25]. The long duration required for supply of replacement parts can lead to long downtime even if such devices could be acquired in the developing economies [25, 26]. These technologies are also complex in nature such that when just borrowed and adopted in its current state in developing economies may result in higher operation costs in case of breakdowns as technical experts need to be imported for their maintenance due to lack of local expertise [1, 6].

As a result of the above discussions, the current study makes two pertinent contributions that aid in attaining sustainable development goals. Firstly, the study aims to promote electricity access to the off-grid rural developing economies using low-cost technology developed from locally sourced and available materials. The study established that rural areas especially in developing economies have low electricity demand and therefore are unfeasible economically to be connected to the grid [10]. In order to alleviate such population from the perennial electricity poverty, rural areas located within the proximity to rivers can benefit from the low-cost current energy conversion technology developed using locally available materials. Locally made systems using available materials and components cannot achieve greater efficiency, however, the priority on the provision of the service is the point of interest. This basic service is more useful than having none at all [6, 24]. This low-cost device may prove an eco-friendly option for extracting hydrokinetic energy from the local rivers.

Secondly, the current study investigates the crucial role of knowledge transfer and capacity building in ensuring the sustainability of local projects meant to benefit the local population. Community engagement in community-based projects promotes the acceptability of the project and interest to be associated with the proposed projects continuity. Providing training on managing the projects and collaborative efforts with the local institutions enhances the sustainability of local projects [28, 29]. This would ensure that the projects' operation is not affected even when the external experties exit the local areas.

Basing on this consideration, this experimental research study was conducted using a prototype low-cost HKT to assess its performance in the field conditions. The research study aimed at investigating the potential of using electronic wastes (e-wastes) and other off-the-shelf materials (locally available materials) to develop a HKT for electricity generation that can meet the service level requirements typical for the rural households using shallow river with low flow velocities in Kenya. This paper therefore presents the field experimental assessment and findings of the low-cost HKT system developed. The low-cost hydrokinetic turbine has the possibility of upscaling and be reproduced in other rural areas to provide electricity access to rural communities in developing countries to enhance universal access to electricity globally.

## 2. Materials and methodology

### 2.1. Background

In this study the field investigation process of a shrouded turbine was done after a suitable shroud structure was selected before based on the laboratory test performances. Previous research conducted in this field have

**Figure 1.** The developed prototype ready transportation using a 3-wheeler vehicle (left); for operation tests in the river (right). Photo credit: Authors.

intensively focused on the improvement of efficiency of particular turbine components under test. This results to complex outcomes that increases the cost of the turbine. In this field investigation, the focus is based on the construction of a small-scale HKT suitable for the equatorial rivers making use of the off-the-shelf materials to aid in the capital and operational cost reduction. The prototype HKT developed in this study is shown in figure 1. The prototype design incorporated the capability of transportation using locally available means, deployment and recovery of the system from the river. This application, when adopted for a real-life pilot testing, would also allow recovery of the system for repair and maintenance purposes in the future applications.

## 2.2. Study site

The experimental field test case study was conducted at River Isiukhu in Kakamega County located 360 km west of Nairobi, the largest capital city of Kenya. River Isiukhu originates from Kakamega forest and drains into River Nzoia that flows into Lake Victoria, the second largest freshwater lake in the world. The HKT test site at River Isiukhu (figure 2) was located at the area whose geographical coordinates lie between 0°15’17’ N and 34°45’02’ E at an altitude of between 1240 metres and 2000 metres above mean sea level. The catchment area receives bountiful amount of precipitation ranging between 1280 mm to 2214 mm annually [30].

## 2.3. Component selection

### *2.3.1. Turbine rotor and generator*

A decommissioned boat motor by the Sportrend company having a 0.24 m diameter rotor with 3-swept-back blades was used in this case figure 3(a). A rotor with swept-back blades is ideal as it is a commonly used propeller for the fishing boats and it can effectively avoid tangling with the weeds in the water [6], but also has the ability to slice the entangled weeds to smaller pieces which is washed away easily. A horizontal axis type arrangement was selected for this study as it offers a better self-starting capability, higher speed and efficiency [7, 33, 34]. The selected rotor has a low solidity and is anticipated to operate at high tip-speed ratio when subjected to high flow speeds.

The motor was operated in reverse mode in this case as generator as shown in figure 3(b). The generator specifications and the rotor details and dimensions are outlined in tables 2 and 3 below. With a rated power of 1000 W at rotor speed of 1350 rpm the motor is thus considered a high-speed motor. The generator is made up of AC brushless permanent magnets. The decommissioned boat motor used is considered as an e-waste that would have potential environmental concerns as their disposal in developing countries are not properly enacted. Its selection for use as a recycled electrical appliance makes it an inexpensive component which are readily available in the developing economies.

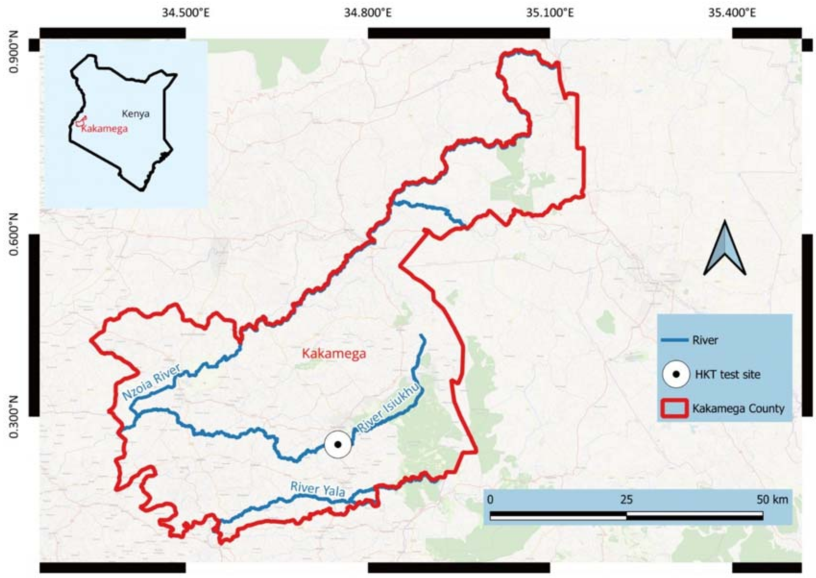


**Figure 2.** Location map of river Isiukhu in Kakamega county showing the test site of the HKT (source: figure generated based on the available resources used with the permission obtained from [31, 32]).

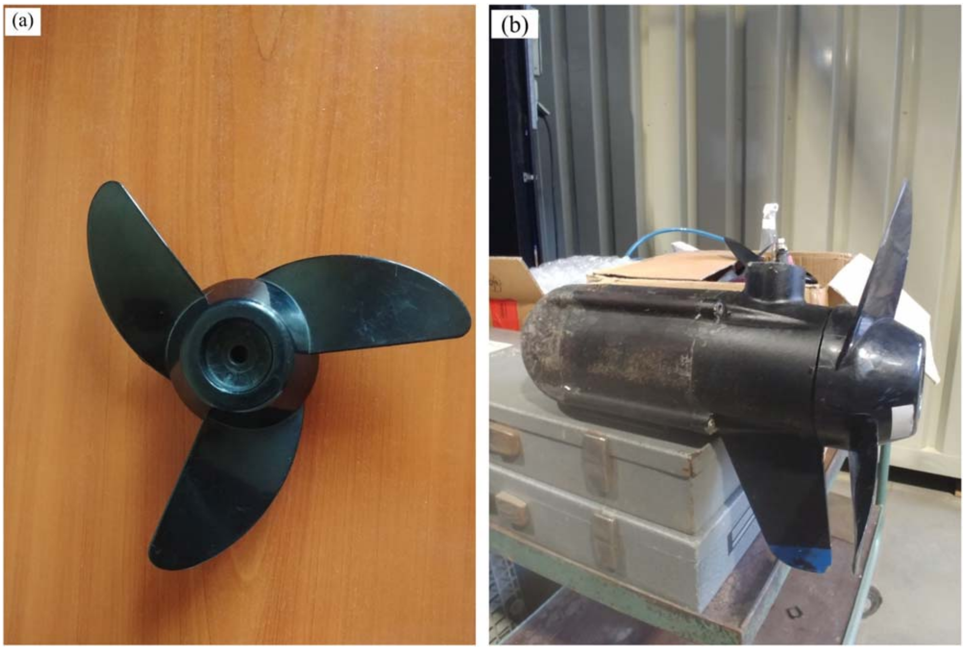


**Figure 3.** (a): 3 swept-back rotor blades, (b): the motor used as a generator.

**Table 2.** Motor specifications.

| Description | Value |
|---|---|
| Rated power | 1000 W |
| Rated speed | 1350 RPM |
| Voltage in | 24 V |
| Maximum current in | 60 A |
| Efficiency at maximum power | 68% |

**Table 3.** Design details and other parameters.

| Description | Dimension | Unit |
|---|---|---|
| Rotor (blade) diameter | 240 | mm |
| Blade tip clearance | 17.5 | mm |
| Nozzle length/extension length | 500 / 200 | mm |
| Inlet /outlet diameters | 450/ 400 | mm |
| Throat diameter (rotor position) | 275 | mm |

#### *2.3.2. Construction of flow acceleration and mounting structure*

The selection of the various forms of the shrouds e.g., diffuser, nozzle and cylinder were informed by the need to ascertain their performances based on pressure recovery, flow direction capability and velocity profiles. The use of diffusers enhances the flow rate through the turbine by creating a low-pressure zone at the exit plane thus drawing in more flow. Similarly, nozzles characteristics of gradual change in the cross-sectional areas accelerates the flow velocity towards the exit. Nozzles and diffusers aid in the rectification of flow by directing flow efficiently and enhancing the hydrodynamic effects [35, 36].

Based on the laboratory experimental tests, three typical hollow augmentation structures were constructed and tested for their performance. The construction consideration and installation procedures are described in works contained in [37]. Nozzle 2 geometry was selected due to its best performance for field test and was reproduced at the production workshop of Masinde Muliro University of Science and Technology (MMUST) in Kakamega Kenya. The nozzle was fabricated using mild steel plates of 1.5 mm thickness. The resulting augmentation structure made of mild steel plate was painted to protect it against rusting when in contact with water. The mild steel plates were selected since they are readily available in the local construction hardware.

A mounting structure for the augmented turbine prototype was constructed using 40 x 40 mm angle profile and painted to prevent them from rusting. The mounting structure measured 650 mm (l) $\times$ 435 mm (w) $\times$ 700 mm (h). This kind of structure allows the flexibility of immersion in water and subsequent recovery for maintenance. The materials for the complete prototype were sourced from the local construction hardware store and cost a total amount of 70 €. The labor cost was 60 € and transportation cost amounted to a total of 60 € during the investigation period. The turbine was donated by the Sportrend and it is anticipated that in the event a turbine was to be purchased from the recycling industry it would cost not more than 100 €, making this prototype to cost approximately 200 €. The complete structure is shown in figure 1.

### 2.4. Experimental set-up

The experimental HKT prototype was tested on River Isiukhu along the Kakamega–Webuye road which is near MMUST. The site was selected for the prototype test as it offered easy accessibility due to its proximity to the road and also was convenient for the researchers since MMUST was the host institution. The river depths and the flow velocity were also found to be favorable for the test prototype at the selected site. The test site location was representative of the local remote areas along the test river, which could not be accessed due to difficulties of the terrain and thus required long planning time to access. HKTs operation mainly depends on sufficient depths and viable flow velocities for complete submergence of the rotor and sufficient rotation to convert kinetic energy to mechanical and electrical energy. Irrespective of the size of a river, lack of sufficient depth and flow velocity renders it inappropriate [38]. River Isiukhu site has these required characteristics which can be found in other local rivers in Kenya and as such was found suitable for use as a test site for demonstration. Since this field work was generally intended for demonstration purposes, the site was suitably selected due to its similar characteristics with the remote areas of interest for future pilot operations such as River Nzoia, River Kuja, River Nyando etc The exercise from construction to field investigations were done between the period of February to April 2024.

The experimental works were preceded by the investigation of flow velocities and water depths across the river channel for a suitable HKT location/siting. The flow velocities across the river were measured using the OTT Type C2 '10.150' small mechanical current meter together with the OTT Z 215 Counter Set (Kempten, Germany) for registering the velocity point measurements with a preset time (in this case 60 s) to obtain the number of pulses. The output was easily read from the LCD double display of the Counter Set showing simultaneously the pulses and time. The flow velocities were then estimated using the calibration equation (2.1) expressed below:

$$v = aN + b \tag{2.1}$$

Where N represent the number of propeller revolutions per second (N, rps) of the meter, v represents the flow velocity (m/s), a & b are coefficients determined by the calibration in an experimental flume (determined from rating of the current meter).

Before the experiments were started, the river flow measurement was done using the mechanical current meter described above to determine the flow velocities at the time of the exercise. At the maximum flow velocity positions with adequate depth for the HKT set-up, several measurements were taken, averaged and used as the river flow velocity for the power output measurements. The experimental set-up was then oriented to the flow such that the rotor began the rotation and the set-up fixed in position for the rest of the operations and measurements.

VOLTCRAFT VC281 TRMS Multimeter Digital CAT III 600 V (±0.9%) with voltage measurement range for both the AC and DC of 0.1 mV–600 V and frequency range of 45 Hz -400 Hz was used to measure both the voltage produced and the rotational frequency which was converted to rotation per minute using the appropriate conversion formula shown in equations (2.2) and (2.3). This method was used instead of the conventional use of the tachometer since the rotor was submerged in the water. A total of eleven resistors with 8 ± 1% Ω resistance connected in parallel were used as loads. The no-load rpm was determined when the device had no loading at all and the full-load rpm was measured with the device loaded with the 8 Ω resistor. The difference between the generator rotational speed when fully loaded and when not loaded is referred to as the rpm slip. The voltage produced by the generator was also measured using the same digital multimeter device. A no-load experiment was performed first, then followed with a load test. Maximum voltage was registered when a single 8 Ω resistor was used and this was adopted as the load for use in this investigation. The rectification of the AC voltage produced was done using the switching electronic board. Both the AC and DC voltages were measured and recorded before and after the rectifier respectively.

$$no - load\ rpm = \frac{120\ *\ f}{p} \tag{2.2}$$

$$full - load\ rpm = \frac{120\ *\ f}{p} - RPM\ slip \tag{2.3}$$

Where f represents the frequency (Hz) and p represent the number of poles of the motor.

### 2.5. Mechanical power extracted from the water

Conversion of water energy from kinetic to mechanical energy using rotors cannot be 100% successfully achieved. The power extracted from the water stream by an energy converter is normally less than the available / or the theoretical water power $P_{water}$ as the power achieved by the energy converter $P_{converter}$ is computed as the difference between the power in the moving water before and after the converter [39]. The power density of the hydrokinetic turbines increases with the cube of the flow velocity and as such high flow velocities have great impact on the power generated [25, 38]. Various state of the art hydrokinetic turbines industrially manufactured have been intensively described and their performances compared [25]. As presented by equation (1.1), the mechanical power of the turbine is assessed by the performance power coefficient denoted by $C_{p,}$ describing the hydrokinetic turbine's efficiency (-). The $C_p$ is determined as the ratio of the mechanical energy converted by the turbine to the kinetic energy of the water flow intercepted by the turbine's cross-sectional area [40]. The $C_p$ has a theoretical maximum value of 0.59 as was determined by Betz and hence known as the Betz limit [6, 41] and is denoted by:

$$C_p = \frac{T_\omega}{0.5\rho A V^3} \tag{2.4}$$

where T is the torque generated by the turbine (in Newton-meters, Nm).

The tip speed ratio (TSR) also helps determine the effectiveness of the turbine runner. TSR is determined as the ratio of the peripheral velocity of the runner ($U = \omega r$) to the inflow mean inlet speed (v) and defined in the equation (2.5).

$$TSR = \frac{\omega r}{v} \tag{2.5}$$

Where Ω represents the angular velocity of the runner (rad/s) = $rpm\ *\ \frac{\pi}{30}$, r is the radius of the rotor (m), v the mean approach flow of water (m/s).

The power output of the turbine prototype was determined by the use of electrical calculation formula shown in equation (2.6) below:

$$P_{electrical} = \frac{V^2}{R} \quad (2.6)$$

Where V is the output voltage measured and R is the load resistance (Ω) and P is the electrical output power in watts.

### 2.6. Techno-economic feasibility

In order to establish the techno-economic feasibility of the current work, a rural off-grid community in the study area in Kakamega is selected. The hourly energy usage of this community is assumed by using a synthetic hourly load data generated from the estimated daily load. A rural household service level power demand of 1.5 kW (a total of 10 households was assumed) when using the essential devices like televisions, radios, energy saving lamps and mobile charging services was selected for the analysis purpose [6, 42]. Homer uses default random variability to estimate realistic load demand from a given load profile since the load cannot follow same pattern on a daily basis. To cater for the variabilities, a daily variation of 10% and hourly variation of 7% was adopted to simulate the realistic variability of the load profile. Homer then generated a peak load demand of 8.86 kW from the scaled annual average energy of 47.70 kWh day$^{-1}$ estimated for the ten households.

Since the present HKT lacked intensive power curve, a vital hydro-resource that is necessary for HOMER analysis of the feasibility of the HKT, the characteristics power curve of a Smart Hydro turbine of 5 kW rating with a maximum output power at 3.1 m s$^{-1}$ tested in a towing tank was used. The assumption made is that the present HKT described has 0.0576 the swept area of the Smart Hydro turbine and as such is expected to produce about 0.0576 as much power under similar flow velocity conditions [6].

Site specific design data for the hydro and solar resources were established from the Homer Pro in-built functions and used for the respective analysis. The fuel price for diesel-generator was estimated at $ 1.298 according to the prevailing local prices as at 18$^{th}$ November 2024 (https://globalpetrolprices.com/diesel_prices/#hl75). The various design specifications of the system types and configurations are presented in the table 4.

## 3. Results and discussion

### 3.1. Background

This study mainly dealt with the investigation of the rotor hydrodynamic performance based on the field prevailing conditions. The parameter of concern was the power generated that was measured in terms of the voltage output (and converted into electrical power output in Watts) based on the rotational speed of the rotor in both the unloaded and loaded conditions. The experimental uncertainties of the measured data were determined by calculating the standard deviation and standard errors of the measurements. The uncertainty in the voltage measurement was calculated using the formula of equation (3.1) and the uncertainty in the power output was determined using equation (3.2). The findings are reported as the mean ± the standard error as presented in table 5 in section 3.4 The determination of the component's efficiencies was based on the water to wire efficiency only. It is expected that the performance of the device developed in this article to be far below those of industrially developed and manufactured HKT devices due to lack of optimization and efficient production.

$$\alpha = \frac{\sigma_N - 1}{\sqrt{N}} \quad (3.1)$$

$$U_y = \frac{\sqrt{\sum \left(\frac{\partial y}{\partial_{Xi}}\right)^2 U_{(x)i}^2}}{y} \quad (3.2)$$

Where $\alpha$ represents the standard error (standard deviation of the mean), $\sigma_{N\text{-}1}$ denotes the standard deviation and N denotes the sample size. For the power output uncertainty equation, y represents the experimental result, $U_{(y)}$ represents the uncertainty in the experimental result, $x_i$ denotes the various measured physical quantities and $U_{(x)i}$ represents the uncertainty in the measured physical quantities. The measurement uncertainties of the power output amounted to approximately 2%.

### 3.2. River flow velocity

The flow velocity of the river at the selected test site was performed once per week for a period of four weeks in the month of February 2024. Two sections were preselected and the velocity profiles established. The average flow velocity was found to be between 0.5–1.0 m s$^{-1}$ across the test section profiles (see figures 4(a) and (b)). Since the two sections had closely similar flow and depth characteristics, only one section was used for the experimental investigations.

**Table 4.** Technical and economical characteristics of the energy sources.

| Component | Parameters | Value | Units |
|---|---|---|---|
| PV | Rated capacity | 0.3 | kW |
| | Efficiency | 21.4 | % |
| | Capital/replacement costs | 400 | $/kW |
| | Derated factor | 88 | % |
| | O&M | 10 | $/year |
| | Operating temperature | 45 | °C |
| | Lifetime | 25 | Years |
| Converter | Capital/replacement costs | 400 | $/kW |
| | O&M | 10 | $/year |
| | Efficiency | 95 | % |
| | Lifetime | 15 | Years |
| Battery | Nominal capacity | 1 | kWh |
| | Nominal voltage | 12 | V |
| | Roundtrip efficiency | 80 | % |
| | Capital/replacement costs | 300 | $/kW |
| | O&M | 10 | $/year |
| | Minimal state of discharge | 40 | % |
| | Lifetime | 10 | Years |
| HKT (present) | Capital /replacement costs | 700 | $/kW |
| | O&M cost | 20 | $/year |
| | Rated capacity | 0.3 | kW |
| | Lifetime | 25 | Years |
| Diesel Generator | Capital/ replacement costs | 160 | $/kW |
| | O&M cost | 0.05 | /h/kW |
| | Fuel price | 1.298 | $/litre |
| | Lifetime | 15000 | hours |

**Table 5.** Summary of electrical output performance of the turbine as generator.

| | No load condition | | 8 Ω load condition | |
|---|---|---|---|---|
| Velocity (m/s) | 0.8 | 1.2 | 0.8 | 1.2 |
| RPM | 1067.723 ± 6.653 | 1219.091 ± 9.289 | 1025.455 ± 4.181 | 1156.363 ± 4.269 |
| AC (V) | 12.577 ± 0.065 | 18.677 ± 0.169 | 9.605 ± 0.089 | 17.224 ± 0.195 |
| DC (V) | 12.866 ± 0.073 | 18.992 ± 0.167 | 10.282 ± 0.053 | 17.715 ± 0.186 |
| Electrical power (W) | — | — | 11.550 ± 0.021 | 37.145 ± 0.021 |
| Water power (W) | 11.583 | 39.092 | 11.583 | 39.092 |
| Water to wire efficiency ($\eta_{wtw}$) | — | — | 0.99 | 0.95 |

During the test period, occasional rainfall events were experienced in the region. The flow velocity obtained for the period was averaged and recorded as the mean flow velocity of the river. Since flow characteristics are expected to change with time, random velocity measurements were done along the pre-established test location profile and the velocity obtained recorded as the mean flow velocity for the duration of running the experiments. The flow velocity slightly varied each day of the experiment and this resulted to varied performance of the device.

### 3.3. Hydrodynamic performance

The mechanical shaft power was not determined since the torque measurement devices were not available. Instead, the electrical power output was measured and used for the performance evaluation of the device. The maximum power output of the device was the aim of investigation and with the limitation to measuring the mechanical shaft power, this parameter was not measured. The available power that can be captured by the rotor's swept area was calculated using equation (1.1). The calculated theoretical power of water was found to be 39.092 W and 11.583 W at a river flow velocity of 1.2 m $s^{-1}$ and 0.8 m $s^{-1}$ respectively. Using equation (2.5) and flow velocities, v = 0.8 m $s^{-1}$ and 1.2 m $s^{-1}$, $rpm_{0.8\ m/s} = 1025.5$ and $rpm_{1.2\ m/s} = 1156.4$ for the respective flow

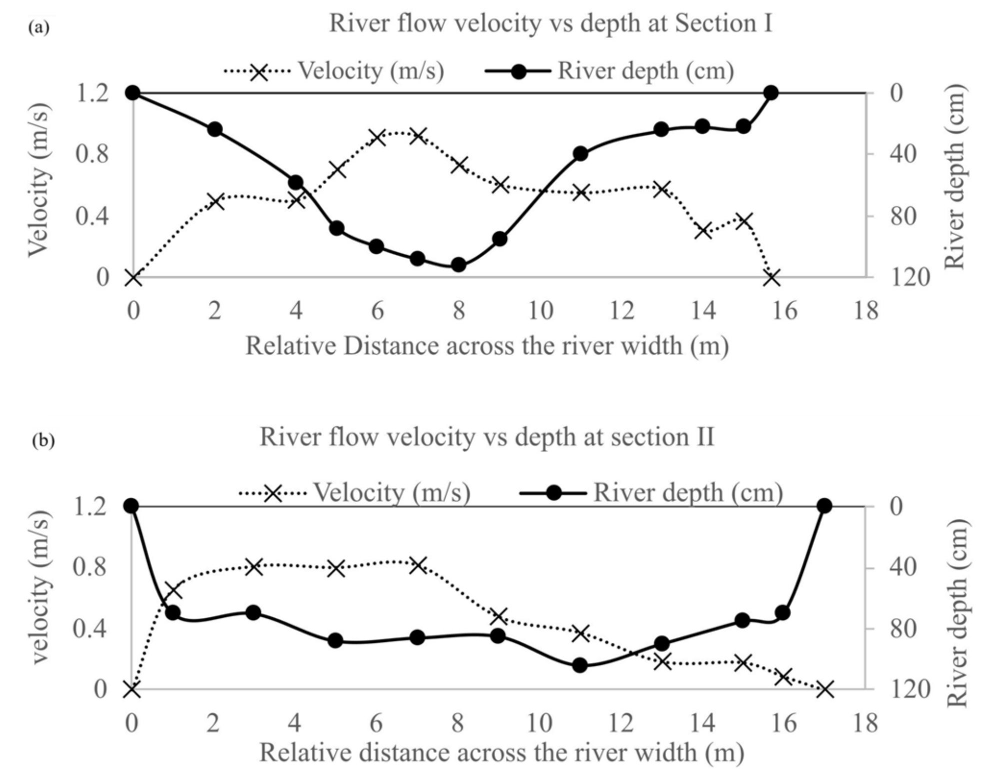


**Figure 4.** (a) Flow velocity profiles at section 1. (b): Flow velocity profile at section 2.

velocities, TSR calculated is found to be 16.11 and 12.11 respectively. The TSR value for a classic 3-blade horizontal axis turbines lies between 6 and 12 [43].

Although the Cp of the turbine performance was not measured due to the limitation mentioned earlier, the electrical performance enhancement realized shows that the use of ducting structure improves the turbines performance to around or beyond the Betz limit by a factor of 1.5–2 compared to the conventional design [44]. The $C_p$ is an essential parameter that outlines the performance coefficient of the HKTs and the wind turbines. Betz established an optimal performance coefficient of wind turbine at 0.593 where the wind turbine achieves the rated power and is regarded as Betz limit [41, 45], with the extractable power available under practical conditions after the losses have been considered estimated at 0.35–0.40 [45]. With uncertainty in the built environment, the performance coefficient of the HKTs and wind turbines are anticipated to vary within the realistic $C_p$ values. The limitation experienced in the current work made it impossible to establish the $C_p$ of the HKT and it is anticipated that $C_p$ values below the documented realistic range defines a reduced capacity factor of the energy converter in consideration.

The performance of the turbine is affected by the mechanical losses associated with the running parts of the machine and the interacting forces. Since the $C_p$ of the turbine was not determined, it is difficult to ascertain the degree of the losses encountered. However, it is necessary to mention that various losses contribute to low performance of turbines. Some of the possible losses include: friction losses in the shaft and the generator gear box, losses due to the blade friction with the water and debris, etc

### 3.4. Electrical performance

Both the AC and DC voltages were measured since the electronic switching board was fitted with the rectifier which was intended for charging the Lithium-ion battery during the normal test runs in the laboratory. The switching board was used in its entirety during the fieldwork and thus enabled the determination of both the AC & DC voltages in the field measurement. The voltage outputs were measured before and after the rectifier thus the AC and DC output.

In the experiment, the rotational velocity of the rotor depends on the load resistance applied. In this case, an 8 Ω resistor was used as a load sample for the test. The turbine performance was tested at no-load condition and when loaded with the sample resistor. In all the cases, the tests were performed for at least 10 min and the results summarized in tables A1–A4 attached in appendix. It can be observed that the performance changes with the load resistance such that for no-load scenario, the voltage measured is higher in comparison to when the load is applied as was determined for the two flow velocities presented in figures 5 and 6. The application of load

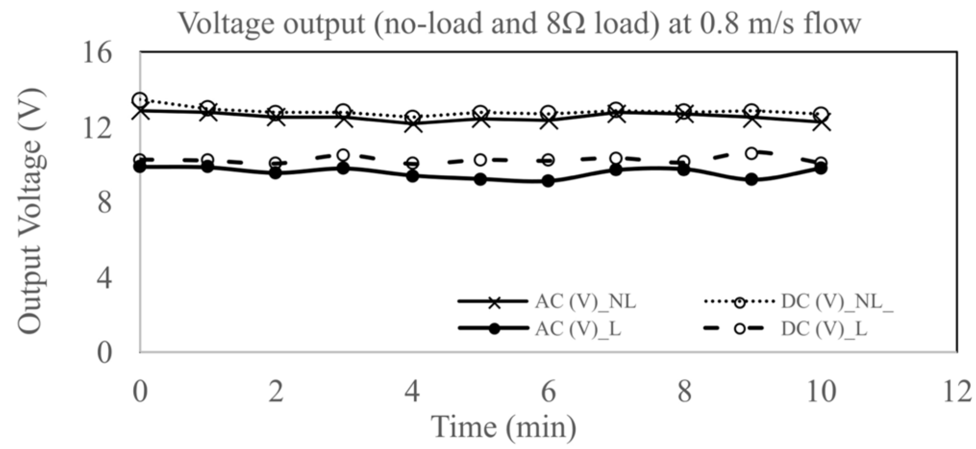


**Figure 5.** Voltage output comparison for load and no-load condition at 0.8 m $s^{-1}$ flow velocity.

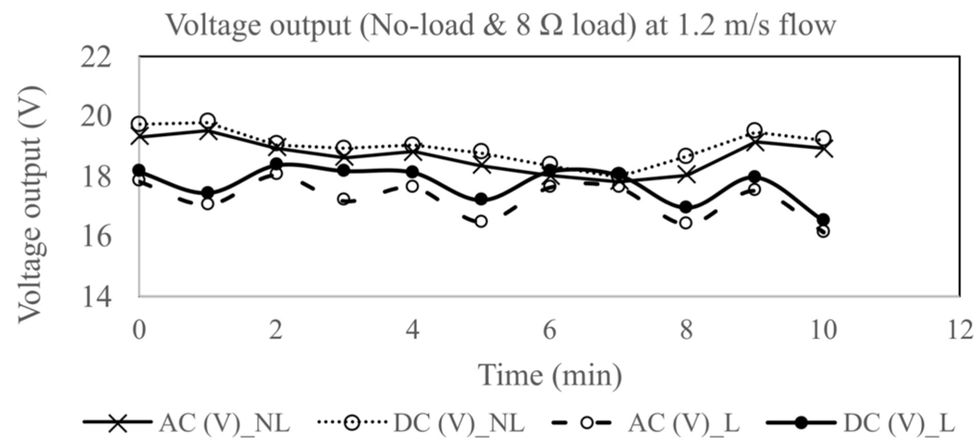


**Figure 6.** Voltage output comparison for load and no-load condition at 1.2 m $s^{-1}$ flow velocity.

resistance results to work done in the generator's coils as the current flow causing Lorentz force to act on the loops of coils. This creates opposing forces on the loop due to the induced current on the loops that results to electrical losses [46]. The works of Rokke and Nilssen [47] concludes that the flux linkages due to induced current density in permanent magnets produced on open circuits is lower than that of loaded conditions and thus the variations in the rotational speed of the motors.

The first no-load test at a flow velocity of 0.8 m $s^{-1}$ registered an average output voltage of 12.577 ± 0.065 V AC and 12.865 ± 0.073 V DC respectively. When a resistor load of 8 Ω was switched on, the rotor rotational speed was dampened and a decrease in the voltage was registered. For the loaded test run, the device registered an average output voltage of 9.605 ± 0.089 V AC and 10.282 ± 0.053 V DC respectively and summarized in figure 5. This is equivalent to 11.543 ± 0.021 W, giving an overall water to wire efficiency of 0.997 (which is about 0.01154 kWh ± 0.210 W).

At a flow velocity of 1.2 m $s^{-1}$, the no-load output voltage registered was 18.677 ± 0.169 V AC and 18.993 ± 0.167 V DC respectively. For the load condition using 8 Ω resistor, the average output voltage registered was 17.224 ± 0.195 V AC and 17.715 ± 0.186 V DC respectively as summarized in figure 6. This is equivalent to an electrical power output of 37.129 ± 0.021 W or 0.03713 kWh. The overall water to wire efficiency is found as 0.95.

The associated power output of the system at the flow velocities 0.8 m $s^{-1}$ and 1.2 m $s^{-1}$ respectively were calculated using equation (2.6) based on the data collected. A graphical representation of the calculated power output is as shown in figure 7. The overall water to wire efficiency is exemplary high as compared to the results obtained in close to a controlled experiment with a water to wire efficiency of about 0.2 conducted by Anyi and Kirke [48]. A similar investigation was done in Sarawak, Malaysia using locally sourced materials by Tan *et al* [6] and obtained of 0.29 and 0.34 by using two forms of same fan rotor. The improved performance of the current prototype is attributed to the use of nozzle as a ducting material [49, 50]. The use of the nozzle enhanced the flow

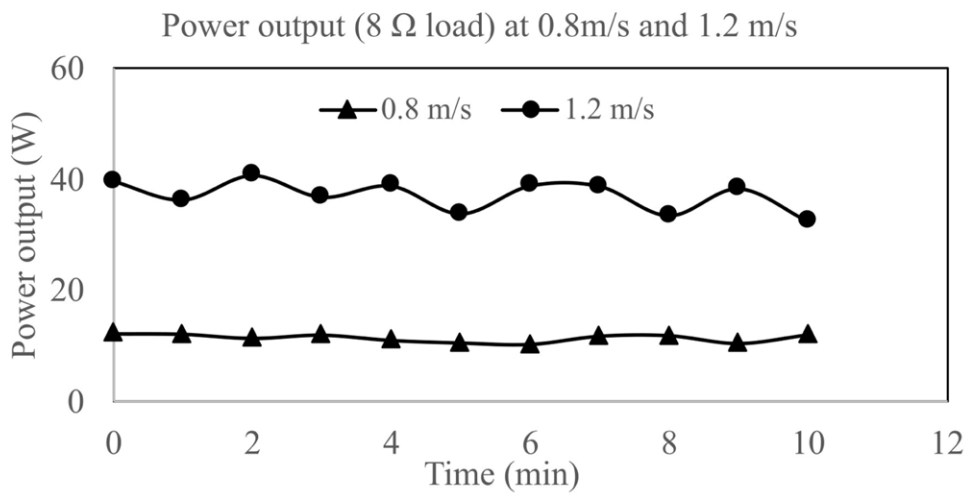


**Figure 7.** Power output characteristic for load conditions at 0.8 m $s^{-1}$ and 1.2 m $s^{-1}$ flow velocity.

velocity directed onto the rotor blades due to the gradual reduction of its cross-sectional area. This again reduces the pressure towards the rotor [35, 36]. As the duct is combined with a small diffuser for attachment purposes as was intended, it had the positive effect of further reducing the pressure at the exit through the formation of vortex thereby drawing more flow towards the outlet [51]. The summary of the electrical performance is presented in table 5. Additional data is provided in the appendix. Fluctuation in the data recorded was observed during the operation periods. The fluctuations resulted from the turbulence of the river flow and the likely effects of the submerged HKT device on the flow continuity of the river.

Rivers and/or streams exhibit natural flows and depending on their width sizes, they can allow the overflow or damming/ blockage conditions to be realized when a solid mass is immersed in them. For wider streams/ rivers, immersion of a single turbine structure will have insignificant backwater effect or damming condition in them. In this case, an overflow condition can be exhibited with minimal rise in head and thus the technology can be described as '*near zero head*' or '*ultra-low head*' turbine systems [38].

### 3.5. Capacity factor

This is an important parameter that is used to define the feasibility component of utilization of renewable energy devices with the HKT included. It is measured as the number of hours during a specific day working of an electrical conversion device working at the maximum capacity in the most suitable operating conditions i.e., water depth and flow velocity for the case of HKTs [52]. Mathematically presented, the capacity factor, $C_f$ denotes the ratio between the electrical energy output of a device over a given period $E_e$, and the electrical energy output it would produce if it operated at its nominal regime during the same period [53]. The Mathematical formula of the capacity factor is given in equation (3.3), where T denotes the duration of the reference period, PR is the rated electrical power of the device and Ee is the electrical output of the device over a given period.

$$C_f = \frac{E_e}{TP_R} \tag{3.3}$$

The $C_f$ as a parameter is the most influenced by the seasonality of the energy resources. For the HKT devices, their performance is found to be optimal in winter/ rainy seasons with 60.15% and very low during the summer/dry seasons at 6.22% and autumn at 5.00%. However, for a $Cf > 20\%$ is considered acceptable for the case of wind energy resources [53, 54].

### 3.6. Cost comparison with alternative off-grid energy sources (PV & diesel generator)

In this section, a demonstrative cost comparison analysis is performed to establish the optimized output using the economic parameters such as Net Present Cost (NPC), levelized cost of energy (LCOE), operating costs and fuel cost for the case of diesel generator. In addition, sensitivity analysis of the present HKT is performed in regards to selected variables in order to understand the performance and behaviour of the system concerning various uncertainties in its input parameters.

#### *3.6.1. Analysis of stand-alone remote energy sources*

A cost comparison analysis of the present HKT technology has been done with PV and Diesel generator. The costs involved determination of the initial capital cost, replacement and operation and maintenance cost. From

**Table 6.** Capital and running costs comparison (US $) of selected energy sources for off-grid areas.

| System | Solar | | | Diesel generator | Present (HKT) |
|---|---|---|---|---|---|
| | PV array | Converter | Battery | | |
| Size | 24.3 kW | 4.6 kW | 69 units | 9.80 kW | 5 units |
| NPC | | 76,589.53 | | 120,006 | 94,080.72 |
| LCOE (kWh) | | 0.542 | | 1.08 | 0.347 |
| Operating cost ($/yr) | | 5,063 | | 18,709 | 9,320 |
| Cost of fuel ($/yr) | | — | | 8829.45 | — |

these cost components, NPC, LCOE and operating costs were established using the HOMER Pro software developed for ascertaining the economic feasibility of energy sources [55]. The optimization performance was then ranked and the most cost-effective option selected based on the least NPC.

The lifetime of the energy system was considered based on the technology selected. The optimization process was done with a discount rate of 6% and inflation rate of 6%. For the non-renewable option using the diesel generator, the fuel price was taken as $1.298/liter based on the prevailing rates in Kenya as at November 2024. The technical and economic data used for the optimization process of the solar PV, present HKT and diesel generator are presented in table 4 under section 2.6. The indicative costs comparisons of stand-alone options for optimal energy supply in the rural off-grid community are shown in table 6.

For the costs determination process, the stand-alone option was considered in this analysis assuming that the incorporation of hybrid system by an individual is deemed to be capital intensive and therefore not affordable. Therefore, the internal rate of return and payback period were not determined since no alternatives were assumed to be available for comparison with the proposed system. Neither of the system produces any income and as such money is spent to build the system and additional operation costs incurred each year [56]. It is evident that the small diesel generator has the lowest initial capital but attracts the highest operation cost compared to PV and the present HKT. Use of HKT ensures round the clock energy supply and can be effectively used with/without energy storage devices and thus lower costs in the long run.

### 3.7. Sensitivity analysis

Sensitivity analysis evaluates the performance and behaviour of a system regarding unforeseen changes it its input parameters. The sensitivity analysis in this case was only considered for the present HKT by evaluating the impact of variation in the flow conditions, material costs and long-term maintenance. The impact of these variations on the NPC and LCOE are analyzed.

The changes in river flow conditions have been analyzed to evaluate the possible effects on the system's NPC and LCOE. The performance of HKTs highly depend on the river flow velocity with the power function having the flow velocity cubed. Thus, the contribution of the HKT energy in the system depends on the flow velocity of the river.

Figure 8 illustrates the effect of variation of river flow velocity on the general NPC and LCOE. It shows that the increasing river flow velocity has a direct influence on the NPC and the LCOE. As the flow velocity increases, the energy generation is enhanced and the NPC and the LCOE decreases linearly. In order to keep the NPC and the LCOE at minimum and enhance the energy conversion of the HKTs during low flow velocities, optimization of the blade design through enhancement of the pitch angle [57]. This does not only improve the performance of the HKT but also anticipated to improve the energy generation even at low flows. Proper selection of components for development of local HKT is important to enhance performance even at low flows. In addition, hybrid hydrokinetic system which combines the HKT with other renewable sources such as wind power or solar PV can offer increased energy generation.

For the case of material costs, the variation in inflation rate was considered as an input parameter since the rate of inflation has a direct cost implication in the production process and as such will influence the cost of materials in consideration. With an increasing inflation rate, the discount rate increases as well. This makes the future costs to be heavily discounted when determining the NPC, leading to a lower present value of the future costs [58]. The LCOE is inversely proportional to the inflation rate. Figure 9 shows that a rise in the inflation rate results to a drop in LCOE.

From the sensitivity analysis determined by Ji [59] about the O&M, he established that the NPC increases as the O&M costs are increased relative to the base O&M cost. The study concludes that higher O&M costs contribute to the overall expenses of running the system. Long term maintenance that results into longer downtime of the system affects the energy production capacity and this will lead to increase in the cost of energy.

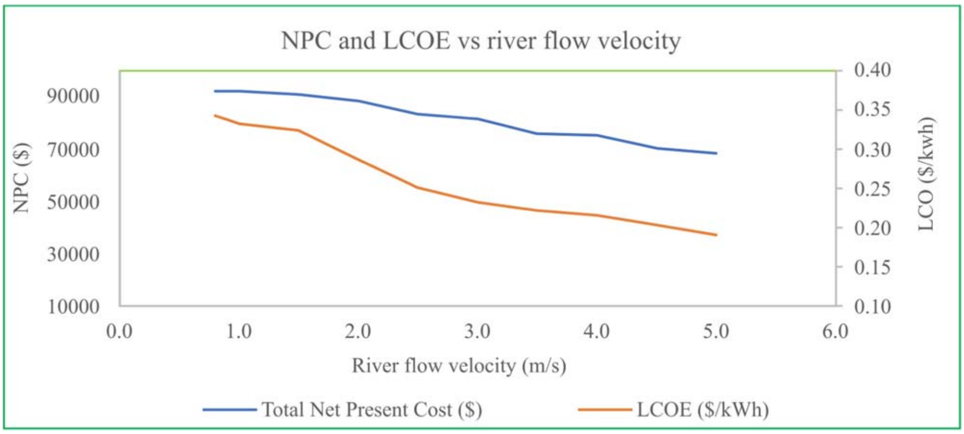


**Figure 8.** Effect of the river flow velocity variation on the NPC and LCOE of the HKT system.

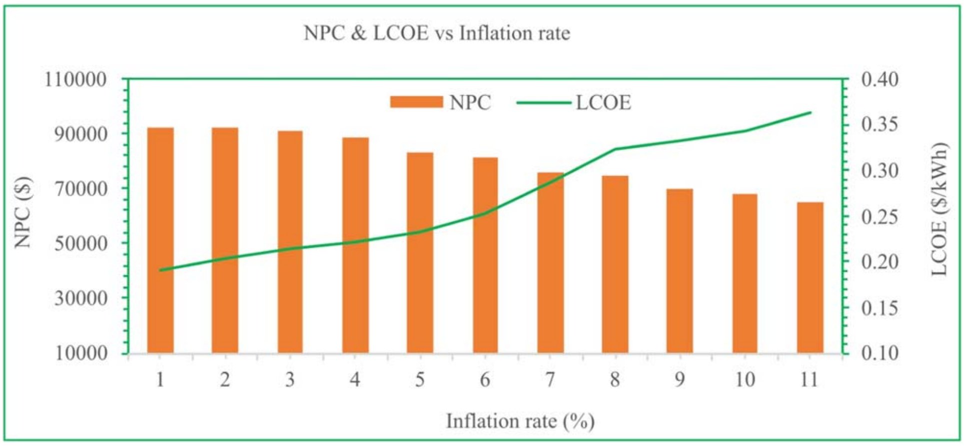


**Figure 9.** Sensitivity of the inflation rate on the net present cost and levelized cost of energy.

Long term downtime would mean that frequent failures occurred that renders the system impractically useful and this lowers its economic viability.

### 3.8. Techno-economic and environmental challenges associated with HKT

The debris accumulation resulting from floating materials is a problem that cannot be avoided and it can lead to damages of the blades and reduced flow through the turbine system since the tropical rivers flow through the jungles thus carry with it logs, leaves and other related jungle trash [34]. The installed turbines can be swept away by flash floods and thus will render the villages to power cut-off. The electrical conversion components like the generators have financial cost attached to them and as such may not be easily acquired by the communities.

The initial investment cost of the technology in terms of workshop production, labour force, regulatory and other amenities for the full functionality of an HKT projects requires financial input and so lack of initial capital outlay in remote developing economies will likely hamper the scalability of the prototype. There is persistent lack of political goodwill in developing economies and with restrictive policies on reproducibility of competing technologies with the state-owned may detrimentally affect the development of these much needed, low-cost technologies in off-grid remote rural areas. Generally, a change in regime will always render incomplete projects in limbo.

Even though the HKTs are considered to pose insignificant effects on the river flow dynamics and habitats especially with the installation of single units compared to conventional hydropower plants [60], still their deployment in arrays have certain environmental challenges. Environmental impacts studies need to be diligently conducted for an informed decision-making process by the project stakeholders and regulatory bodies. The blockage of fish migratory routes is possible where no fish passage is provided for in the array installation of HKTs. Existing research to date points out that blade strikes still poses a serious problem to the marine life. Even though most cases reported that marine life avoids the turbines altogether, the few cases observed that when a fish pass through the turbine swept area there is a survival rate of 98% as demonstrated in [61, 62]. HKT arrays induces an upstream damming effects and thus will result to sediment depositions and subsequent sediment deficit due to bed scouring on the downstream caused by high exit flow velocities [63]. In addition, from the HKT arrays modelled in tidal environment by Ahmadian *et al* [64], it is stated that such an arrangement could impact suspended sediment concentrations at downstream distances of up to 1.6 times the array length. Similarly, it is reported that the sediment transport can affect the array performance and the anchoring integrity of the structures. Also, large dunes develop and change with the flow patterns and an introduction of turbines can possibly alter the creation of theses dunes and associated troughs in the river bed [65]. Further areas of environmental concerns that need attention are (1) construction spills and device leakage effects n water quality, (2) effects of electromagnetic fields on the marine life, (3) habitat alteration due to the introduction of artificial structures, (4) benthic predators' ability to find prey [62, 66, 67]. However, these environmental issues can be mitigated through precautionary measures in place such as avoiding their deployments in the most sensitive and fragile sites to reduce the effect on the biodiversity. In addition, careful selection of the construction materials should be taken into consideration to avoid introduction of hazardous components into the water bodies [19].

### 3.9. Capacity building and sustainability

Community based projects exhibit considerable potential when the community members are involved in the development of projects within their locality. It is authentic that any village will gladly accept a free offer of a hydro-electric scheme but this does not mean that they would make good use of it. Their contribution in the project through provision of labour or cash contribution will enhance their commitment to the project. The local community can volunteer their labour freely in the Harambee spirit to provide services like cleaning of the turbine from debris and any other activities that may require their attention and input. Local based development projects having an element of community funding has turned out to be the most reliable and fully utilized [68]. It is therefore necessary to conduct community meetings with the local residents to discuss the proposals and engage their level of interest and commitment [18].

It is imperative that great care be taken to ensure well management of village hydro-electric programmes especially when owned by the community. Identification of potential persons to be charged with the responsibility for the running of the scheme is very vital unlike when the responsibility is blindly left to the community. Two people at a minimum to be trained as operators from the initiation of the project in order to complement each other in case one person is not available. Comprehensive training should be provided along with a well-illustrated step by step manual developed for the scheme. Similarly, technical skills need to be provided to the locally trained persons who can handle the multi-disciplinary skills such as electrical, mechanical and civil works. This will ensure that the routine maintenance of the system can be undertaken on regular basis as need be and that the maintenance and operation costs are minimal as the presence of local personnel eliminates the long waiting time for an expert from the cities or abroad. Locally trained individuals from the technical and vocational training institutes are available in Kenya and therefore their training on operationalization of such a system should not be a problem. In addition, continuous training and development programs through the collaboration between the local development projects and institutions of higher learnings in developing countries need to be enhanced. Through such initiatives, the local project stakeholders can benefit from the Research and Development (R&D) output to improve on the operation, maintenance, development of local prototypes and scalability of the existing initiatives.

The production process, labour force, regulatory permits and other amenities require financial input and as such inadequate initial capital is likely to hamper the scalability of the prototype. The willingness of national and local government in providing the initial capital outlay of the community projects is necessary. In Kenya for instance, government agencies provide financial support for rural development by financing the local groups to initiate a project. A detailed proposal submission and proof of registration of the local group and the constitution are the mandatory requirements. However, this also depends on the political goodwill but should not discourage the use of alternative methods of financing the local projects. There exist the small and medium enterprises (SMEs) loan facilities for organized groups and this can be an option for the local HKT hydro-power projects. Local industries when approached provide financial support to local groups for the local projects through the corporate social responsibilities functions. Donation and subsidies from the NGOs such as the USAID and the GIZ through BMF have supported local development agendas and as such are viable options that rural HKT development scheme which is locally owned can get financial aid and subsidies. Similarly, communal contribution act as an initial source of funding where the commitment and acceptance of the project is exhibited.

It is obvious that the use of repurposed e-waste components is inefficient and require frequent replacements. However, with the existence of large recycling industry in most developing countries, their availability is certain.

Similarly, low-cost and low rpm generators such as the permanent magnet axial flux generators available at wind windpmg.com can be used and offer higher power generation with long life span. The fabrication of other components can be achieved locally to reduce the cost and have a promising power generation. Where possible the use of renewable hybrid system can be adopted for large demand loads.

*3.9.1. Future sustainability prospects*

HKTs provides alternative options for the provision of renewable energy for the off-grid communities in developing economies. The population in these areas have low income and require low amount of energy at the same time. Future increase in demand cannot be avoided and despite the challenges that developing nations or the neglected population experience, the developed prototype should be appropriate to offer the much-needed solutions. To cater for the anticipated demands, the following prospects are considered for future improvement by considering and adopting the approaches outlined by Klunne in [69, 70]:

Infrastructure development: the current infrastructure is a mini scale and can only support a small population. It is envisioned that a wider coverage can be effectively supported through identification of viable sites and replication of the prototype to serve the nearby population. This can be achieved through collaborative approaches that encourages technology transfer.

Financial sustainability: with upscaling of the technology, there are significant increase of expenses to meet the development and operation of the technology. to support the financial sustainability, it is envisioned that diversified revenue sources such as members subscriptions and partnerships be considered. Local development financial supports such as the savings and credits facilities and low interest loans are alternatives that can be tapped into.

Technical sustainability: the involvement of locally trained expertise in providing technical skills to maintain the system creates an enabling environment for the local community to provide technical solution by themselves.

## 4. Conclusion

Hydrokinetic river turbines (HKTs) are potentially viable for adoption for extracting kinetic energy from the flowing water such that limited to no civil works are undertaken. This technology is essential in promoting off-grid connectivity to remote villages found within the developing economies where economic feasibility does not favour grid connection initiatives and provision of the service is of priority regardless of the efficiency for a small household living near the rivers. The ultimate goal of this research is not in achieving high energy quantities or efficiencies, but to demonstrate that small amount of energy urgently needed in local off-grid communities in rural developing economies can be achieved using locally available and inexpensive components.

This article has demonstrated the suitability of a low-cost technology developed using a decommissioned boat motor operated as a generator, a component which was considered an e-waste. With the aid of a nozzle to accelerate the incoming flow, the performance of the technology was enhanced and the power extracted can be utilized within the local areas for beneficial activities such as phone or battery charging. With possibility of upscaling, this technology can sustainably provide a 24 h energy supply, sufficient to charge batteries/solar lanterns during cloudy seasons in the village or provide direct lighting connections in the houses and security lights within the villages. Small amount of electricity is sufficient to enhance the socio-economic wellbeing of the society in rural areas and such a low-cost technology that utilizes local materials can be very resourceful in eliminating the over-reliance on diesel generators to provide the much-needed services in the villages.

Additionally, the sustainability of the technology would be enhanced by providing technical expertise empowerment to the local community through hands-on training of selected local members. This can be achieved through capacity building in the form of imparting hands-on skills requirements for the operation and maintenance of the system. This would ensure that the operation and maintenance of the technology does not end with the departure of the creator. The related operation and maintenance costs will be reduced as hiring of external expertise is reduced through training of local experts.

From the economic point of view, the use of solar PV seems the best renewable option compared to the current HKT; however, the PV output is expected to fluctuate with the fluctuating solar irradiation. The use of HKT provides a cleaner option compared to diesel generator and a cheaper option in the long run as it requires no storage and ensures round clock energy supply.

## 5. Future directions

This article presented the field experimental investigation of locally developed low-cost energy conversion HKT using off-the-shelves materials and recycled electronic components like decommissioned boat motor as a generator. The aim of the experimental investigation on usability of such components has been demonstrated. Large energy generation and higher efficiencies were not considered in this regard. However, the output has invoked further interests that were not envisioned and are therefore proposed for future research. The following future directions for better understanding of the technology are proposed:

- Analysis of the technology's power output in a broader range of flow velocities to derive the device's power rating and power curve.
- Evaluating the device's power coefficient in reference to the Betz limit
- In-depth cost benefit analysis of the technology, challenges and associated risks.
- Development of end-user design and operation manual for sustainability at the local village set-up.

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## Conflicts of interest

The authors declare no conflict of interest in this research.

## Funding

This research received no external funding.

## Appendix

This section provides additional data colleted and analyzed for this research article and used to generate some of the graphical data presentations outlined. A complete data useful for further analysis are hereby provided in table format.

**Table A1.** Data output at 0.8 m $s^{-1}$ flow for the no load scenario test.

| Time (min) | Frequency (Hz) | Rotation speed (rpm) | AC (V) | DC (V) |
|---|---|---|---|---|
| 0 | 74 | 1110 | 12.902 | 13.503 |
| 1 | 73 | 1095 | 12.851 | 13.021 |
| 2 | 70 | 1050 | 12.573 | 12.792 |
| 3 | 69 | 1035 | 12.532 | 12.843 |
| 4 | 70 | 1050 | 12.256 | 12.552 |
| 5 | 71 | 1065 | 12.471 | 12.791 |
| 6 | 71 | 1065 | 12.411 | 12.744 |
| 7 | 72 | 1080 | 12.794 | 12.922 |
| 8 | 72 | 1080 | 12.742 | 12.835 |
| 9 | 71 | 1065 | 12.525 | 12.863 |
| 10 | 70 | 1050 | 12.321 | 12.694 |
| | mean | 1067.727 | 12.580 | 12.869 |
| | std dev | 22.064 | 0.216 | 0.243 |
| | std error/ uncertainty | 6.653 | 0.065 | 0.073 |

**Table A2.** Data output at 0.8 m $s^{-1}$ flow for the loaded scenario test with 8 Ω resistor as load.

| Time (min) | Frequency (Hz) | Rotation speed (rpm) | AC (V) | DC (V) | AC power output (W) |
|---|---|---|---|---|---|
| 0 | 69 | 1035 | 9.922 | 10.313 | 12.306 |
| 1 | 69 | 1035 | 9.892 | 10.251 | 12.231 |
| 2 | 68 | 1020 | 9.595 | 10.113 | 11.508 |
| 3 | 69 | 1035 | 9.831 | 10.516 | 12.081 |
| 4 | 68 | 1020 | 9.443 | 10.094 | 11.146 |
| 5 | 67 | 1005 | 9.254 | 10.282 | 10.705 |
| 6 | 67 | 1005 | 9.142 | 10.242 | 10.447 |
| 7 | 69 | 1035 | 9.754 | 10.374 | 11.893 |
| 8 | 68 | 1020 | 9.793 | 10.165 | 11.988 |
| 9 | 70 | 1050 | 9.215 | 10.663 | 10.615 |
| 10 | 68 | 1020 | 9.853 | 10.134 | 12.135 |
| | mean | 1025.455 | 9.609 | 10.282 | 11.550 |
| | std dev | 13.866 | 0.295 | 0.176 | 0.703 |
| | std error/ uncertainty | 4.181 | 0.089 | 0.053 | 0.021 |

**Table A3.** Data output at 1.2 m $s^{-1}$ flow for the no load scenario test.

| Time (min) | Frequency (Hz) | Rotation speed (rpm) | AC (V) | DC (V) |
|---|---|---|---|---|
| 0 | 84 | 1260 | 19.322 | 19.724 |
| 1 | 84 | 1260 | 19.514 | 19.791 |
| 2 | 82 | 1230 | 18.935 | 19.044 |
| 3 | 81 | 1215 | 18.631 | 18.910 |
| 4 | 82 | 1230 | 18.804 | 19.012 |
| 5 | 80 | 1200 | 18.344 | 18.793 |
| 6 | 79 | 1185 | 18.015 | 18.343 |
| 7 | 78 | 1170 | 17.835 | 17.990 |
| 8 | 79 | 1185 | 18.043 | 18.645 |
| 9 | 83 | 1245 | 19.134 | 19.482 |
| 10 | 82 | 1230 | 18.916 | 19.213 |
| | mean | 1219.09091 | 18.681 | 18.995 |
| | std dev | 30.8073191 | 0.559 | 0.553 |
| | std error/ uncertainty | 9.2887562 | 0.169 | 0.167 |

**Table A4.** Data output at 1.2 m $s^{-1}$ flow for the loaded scenario test with 8 Ω resistor as load.

| Time (min) | Frequency (Hz) | Rotation speed (rpm) | AC (V) | DC (V) | AC power output (W) |
|---|---|---|---|---|---|
| 0 | 78 | 1170 | 17.834 | 18.135 | 39.756 |
| 1 | 77 | 1155 | 17.057 | 17.421 | 36.367 |
| 2 | 78 | 1170 | 18.055 | 18.353 | 40.748 |
| 3 | 77 | 1155 | 17.171 | 18.163 | 36.855 |
| 4 | 75 | 1125 | 17.634 | 18.112 | 38.870 |
| 5 | 77 | 1155 | 16.462 | 17.183 | 33.875 |
| 6 | 77 | 1155 | 17.636 | 18.143 | 38.879 |
| 7 | 78 | 1170 | 17.622 | 18.021 | 38.817 |
| 8 | 77 | 1155 | 16.380 | 16.922 | 33.538 |
| 9 | 78 | 1170 | 17.522 | 17.954 | 38.378 |
| 10 | 76 | 1140 | 16.128 | 16.483 | 32.514 |
| | mean | 1156.36364 | 17.227 | 17.717 | 37.145 |
| | std dev | 14.1581971 | 0.646 | 0.616 | 2.756 |
| | std error/ uncertainty | 4.26885705 | 0.195 | 0.186 | 0.021 |

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