International Journal of Green Energy

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/ljge20

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To cite this article: Willis Awandu, Jens-Uwe Wiesemann & Boris Lehmann (27 Nov 2024): Village-level hydropower for developing economies: Accelerating access to electricity using low-cost hydrokinetic technology for remote community: 1. Laboratory flume experiment, International Journal of Green Energy, DOI: 10.1080/15435075.2024.2429777

To link to this article: https://doi.org/10.1080/15435075.2024.2429777

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INTERNATIONAL JOURNAL OF GREEN ENERGY
https://doi.org/10.1080/15435075.2024.2429777

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Village-level hydropower for developing economies: Accelerating access to electricity using low-cost hydrokinetic technology for remote community: 1. Laboratory flume experiment

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ABSTRACT
This article presents the feasibility of a low-cost hydrokinetic turbine technology developed and experimentally tested in the laboratory for enhancing electricity access in isolated off-grid communities in the rural areas. The research and development involved using e-waste and locally available materials to develop a modular energy conversion system using rivers' kinetic flow. A decommissioned boat motor with a 0.24 m diameter rotor is operated as a turbine. Four augmentation structures were developed and tested in a flume to evaluate their performance for flow acceleration and application for energy conversion. The four varied configurations produced distinctive performances in an overflow test condition at an approach velocity of 0.25 m/s such that: nozzle 1(8.111 ± 0.107 V DC, 7.116 ± 0.098 V AC), Nozzle 2 (10.038 ± 0.103 V DC, 8.804 ± 0.123 V AC), nozzle 3 (8.523 ± 0.009 V DC, 7.543 ± 0.008 V AC) and Diffuser_type 1 (8.053 ± 0.082 V DC, 7.147 ± 0.144 V AC). Only nozzle 1 was tested in dammed condition and produced 13.248 ± 0.123 V DC and 11.395 ± 0.008 V AC. Nozzle 2 produced a promising performance serving as a reference in comparison to the other three configurations under similar flow conditions.

ARTICLE HISTORY
Received 14 March 2024
Accepted 7 November 2024

KEYWORDS
E-waste; hydrokinetic turbine; low-cost technology; rural areas; off-grid communities

1. Introduction

1.1. Background information

Energy is an important asset for global economic development and is such an essential commodity for the general human socio-economic development in all life sectors such as health, economy, education and the general social life (Fatema and Ustun 2019; Indah and Rarasati 2020). The United Nations' (UN) Sustainable Development Goal (SDG 7) advocacy for the affordable and clean energy access to everyone by 2030 is an indication that energy availability is a basic right that promotes and sustains the overall aspects of human development (Awandu et al. 2022; Dinkelman 2011). Despite the UN aggressive move to ensure that countries fulfill the SDG 7 projection of access to electricity by all by the year 2030, this prognosis seems unrealistic as close to 675 million people still had no access to this basic commodity by 2021, with 84% of the population (566.6 million) living in the Sub-Saharan Africa (SSA) (Awandu et al. 2022; IEA, IRENA, UN, World Bank, and WHO 2022). Sadly, out of the total population that is without access to electricity in Africa, 78% (443.9 million) of the population is found within the isolated rural areas (IEA, IRENA, UN, World Bank, and WHO 2022).

The renewable energy technology considerably offers a cost-effective and sustainable options for rural electrification especially by enhancing stand-alone options in areas with large distances, small population and low energy demand (Allison 2007; IEA 2011; World Bank 2013). Wind and solar photovoltaics have been intensively developed as stand-alone options that can effectively serve the off-grid rural communities. 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 (Tan, Kirke, and Anyi 2021).

1.2. Hydrokinetic turbine technology

The hydrokinetic turbine, a system comprising a compact and modular structure to generate electricity using the kinetic energy of flowing rivers with no elevation is an appropriate means of electricity access in off-grid areas having flowing rivers (Salleh, Kamaruddin, and Mohamed-Kassim 2018). Remote rural areas located within the proximity to rivers can effectively make use of the micro-hydrokinetic turbine systems (μ-HKT) which provides an alternatively economical and reliable electricity option (Paish 2002). This compensates greatly for the non-continuous availability of related small-scale renewable energy technologies like solar photovoltaics and wind turbines (Vermaak, Kusakana, and Koko 2014). The hydrokinetic technology provides an alternative option to the conventional hydropower electric generation by utilizing the kinetic energy of flowing water instead of the potential head of

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/15435075.2024.2429777

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falling water to generate electricity (Niebuhr et al. 2019; Yuce and Muratoglu 2015).

The technology share similar physical principles with wind turbine systems in operation, electrical hardware and variable speed capability for optimal energy extraction (Zhou 2012). Water is denser than air almost 800 times (density of water = 1000 kg/m^3, density of air = 1.2 kg/m^3) and this provides an advantage on the capability of energy extraction using the hydrokinetic turbine (HKT) systems even at low speed (Kuschke and Strunz 2011; Vermaak, Kusakana, and; Koko 2014; Maniaci and Li 2012). The hydrokinetic technology is more attractive among other renewable technologies due to its predictability compared to wind and solar that depends on the daily weather conditions (wind and solar availability) while the HKT operates 24/7 as long as there is flow in the streams/ rivers; and also causes minimal environmental impact since minimal to no civil engineering works are required (Elghali, Benbouzid, and Charpentier 2007; HAE 2023). The kinetic energy of the continuously flowing water is directly utilized through conversion into electricity by placing a hydrokinetic energy converter inside the water body (Vermaak, Kusakana, and Koko 2014; Tan, Kirke, and Anyi 2021; Yuce and Muratoglu 2015). The theoretical power generated by the hydrokinetic turbine (HKT) system is determined in a similar manner as that of wind turbine system using the equation *1.1* below:

$$P = 0.5A\rho V^3 C_p \tag{1}$$

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) and C_p is the efficiency of the turbine (-), and it has a theoretical maximum value of 0.59 as was determined by Betz and hence known as the Betz limit (Elghali et al. 2007; Tan, Kirke, and Anyi 2021).

Several research and developments have been attempted in order to improve the performance of the available HKT systems based on design optimization, turbine placement, augmentation and techno-economic feasibility (Kumar and Sarkar 2016; Salleh, Kamaruddin, and Mohamed-Kassim 2018). In this regard, numerous companies in the USA, Canada, Australia and Europe continue to develop hydrokinetic turbines to harness the tidal and river kinetic energy. Such high-end market-oriented technologies are too expensive for the people who really need them especially in the African and Oceanian continents where the rural communities rarely have the purchasing power to acquire the technology (Table 1). In case of breakdown during the operation, the long duration for supply of replacement parts can lead to long downtime (Kirke 2020; Salleh, Kamaruddin, and Mohamed-Kassim 2018). Technical experts need to be imported for the maintenance due to lack of local expertise and this further increases the operation and maintenance (O&M) costs (Awandu et al. 2022; Tan, Kirke, and Anyi 2021).

Commercially developed turbines are typically designed for flow velocities of 3 m/s and above basing on the best tidal sites. However, most rivers in rural areas have flow velocities not more than 1 m/s most of the time and so such turbines may deliver below their rated power (Kirke 2019, 2020). Some locally developed HKT turbines suitable for the local site conditions have shown the capability of providing access to the much-needed electricity at low capital and operation costs. A horizontal axis HKT developed for the electrification of rural community in Sarawak is a good example of the locally made low-cost technology for a service level deemed sufficient for a rural setting having no such commodity (Tan, Anyi, and Song 2020). The prototype developed provides the opportunity of delving in the "do it yourself (DIY)" in making use of the locally available materials for promoting access to electricity in off-grid locations.

This paper therefore seeks to address the access to electricity challenges by remote rural community in developing countries as follows:

(a) Explore the suitability of using local materials to develop low-cost energy conversion system.
(b) Develop a small-scale HKT suitable for shallow rivers in remote off-grid areas using a decommissioned boat motor as a turbine and generator.
(c) Establish the potential sustainability options by promoting capacity building for local production of the technology.

Efficiency of the technology was not emphasized in this study as this cannot be achieved with the local production of such a low-cost technology to perfection (Tan, Kirke, and Anyi 2021). Rather a priority on the provision of access to electricity – that is having an electricity source that can provide very basic lighting, charging a phone and power a radio for 4 hrs per day (Ritchie, Rosado, and Roser 2019) needs to be greatly considered. Basing on this situation, the Chair of Hydraulics Engineering and Hydraulic at TU Darmstadt has conducted a laboratory scale doctoral research study that is aimed at investigating the use of 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 flow velocity of less than 0.5 m/s.

Table 1. HKT power output and prices as at August 2020 reproduced with permission from (Tan, Kirke, and Anyi 2021) under open access rights and contents. © 2021 published by Elsevier Inc. On behalf of international energy initiative.

Company	Rated power, kW	Flow velocity m/s for rated power	Power at 1 m/s	Price, USD ($)
New Energy Corp	5.0	3.0	0.185	50000
Smart Hydro	5.0	3.1	0.168	14000
Idénergie	0.5	3.0	0.018	9875
Green-energy Hydrocat	0.183	1.0	0.183	16600
Waterrotor	1.0	1.8	0.171	5000
EcoCinetic	2.0	3.0	0.074	4900
Ibasei Cappa	0.25	2.0	0.031	12000

Based on the site-specific conditions such as flow velocity and sufficient depths, this prototype can be scaled up to have rotor diameter suitable for the available flow depths to enhance the power output as the power generation is directly proportional to the swept area. The installation of a low-cost hydrokinetic turbine in remote villages can enhance and provide a complementary service to the other small-scale renewable sources such as the portable solar systems that has gained wide use for remote electrification in many parts of the developing worlds. This paper presents the laboratory experimental assessment and findings of the low-cost HKT system developed for possible upscaling and adoption to provide electricity access to remote communities in developing economies.

2. Method

Previous studies have shown that shrouded turbines perform best compared to bare turbines under the same conditions. In this section, the performance of four hollow-structures (shrouds) produced in the workshop was tested. This was done so that a suitable shroud would be selected for use in the planned fieldwork.

2.1. Component selection

2.1.1. Turbine rotor and generator

A decommissioned boat motor by the company Sportrend with a 0.24 m diameter rotor having 3-swept-back blades (Figure 1) was used in this case and operated as generator. The selected rotor has a low solidity and is anticipated to operate at high tip-speed ratio when subjected to high flow speeds. The turbine and generator characteristics are shown in Table 2.

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 (Tan, Kirke, and Anyi 2021). 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. Such recycled components cannot achieve efficient performance but may provide access to electricity for basic usage. The accompanied motor used as generator comprise an AC brushless permanent magnet having the following specification shown in Table 3.

Figure 1. 240 mm diameter 3-swept-back rotor blade.

Table 2. Rotor and generator details.

Description	Dimension	unit
Rotor (blade) diameter	240	mm
Turbine length (generator body)	350	mm
Blade tip clearance	17.5	mm

2.1.2. Development and selection of flow acceleration structures

The selection of the various forms of the shrouds e.g., diffuser, nozzle and cylinder was informed by the need to ascertain their performances based on pressure recovery, flow direction capability and velocity profiles. The use of diffusers enhances flow rate through the turbine by creating a low-pressure zone at the exit plane thus drawing in more flow. Nozzles and diffusers aid in the rectification of flow by directing flow efficiently and enhancing the hydrodynamic effects.

Four typical hollow structures also referred to as shrouds ((see Figure 2(a-d)) were examined in this case comprising conical nozzle-type models Figure 2(b,d) with reducing internal cross-sections, a cylindrical nozzle-type model (referred to as nozzle 1; _Figure 2a) having a constant internal cross-sectional area connected to a short nozzle with a reducing internal cross-sectional area and finally diffuser-type models namely **diffuser-type 1** (Figure 2c) and **diffuser-type 2 (presented as nozzle 3 in reverse orientation)** that expand the internal cross-sectional areas downstream. The two diffusers developed were later used in reverse orientation as nozzle 2 and nozzle 3. The best performing structure would be selected for a planned fieldwork to compare the performances of the HKT for the laboratory and field conditions. The cylindrical nozzle-type model was developed from plastic pipe while the conical structures were made of mild steel plates of 1.5 mm thickness. The resulting augmentation structures made of mild steel plates were then painted to protect them against rusting when in contact with water. The mild steel plates were selected since they are readily available in the construction hardware worldwide and so will be easily sourced.

Conical diffusers were initially developed and fitted with a short nozzle connection which was intended to direct and accelerate the incoming flow toward the diffuser. These structures were then used in reverse orientation as nozzles (**diffuser-**

Table 3. Motor specification.

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

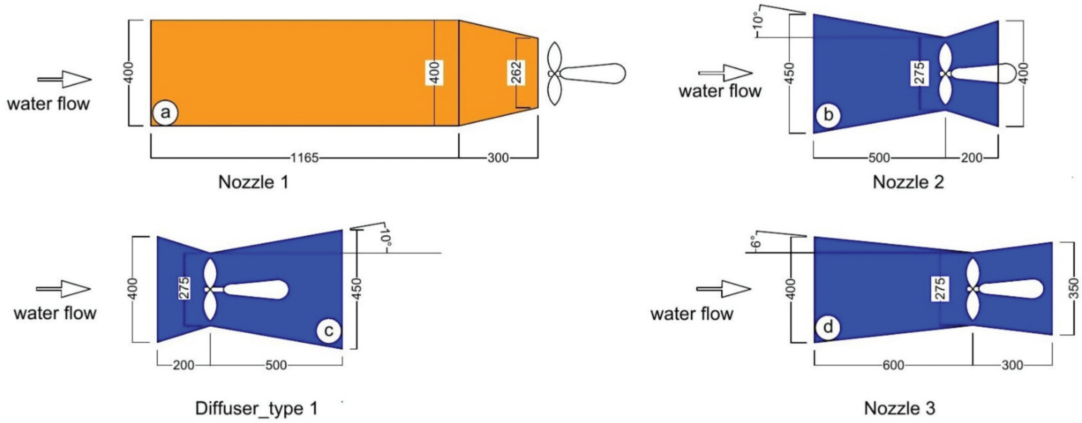

Figure 2. (a) Plastic cylindrical-conical shaped nozzle 1, (b) Frustrum nozzle 2; (c) Diffuser-type 1; (d) Frustrum nozzle 3. Photo credit: authors.

type 1 used as ***nozzle 2*** and **diffuser-type 2** used as ***nozzle 3***) since the configurations matched perfectly with the intended designs of the two nozzles and also to minimize on the material wastage. Diffuser-type 2 model was not put into operation as a diffuser but instead used as nozzle herein referred to us ***nozzle 3***, since the performance of diffuser-type 1 was lower than when it was used as a nozzle (in this case as ***nozzle 2***). The accelerators were then operated as stated and the performance compared when used as diffusers and nozzles for flow accelerations.

The rotor blade (diameter = 240 mm) was positioned at the connection point (throat) between the main structure and the accelerator portion. With a rotor blade tip clearance of 17.5 mm, the diameter of the structure's throat (connection point or position of the rotor) was designated as 275 mm (throat diameter of the structure). The lengths of the two diffusers were determined according to (Anbarsooz, Mazloum, and Moghadam 2020; Ohya et al. 2008) using the range of length ratio L/D = 1.25–2.5, where L is the diffuser length and D is the inlet diameter of the diffuser (in this case the throat diameter). The length ratio chosen was governed by the practical applicability of the shroud as very long augmentation structure would make it difficult to be deployed especially where there is no machinery for lowering the set-up on site, and thus inclusion of a short peripheral appendages has shown a remarkable improvement in performance for using a short-bodied shroud (Ohya et al. 2008). The diffuser's expansion (diverging) angles of **f** = 0°-12° was used in accordance to (Matsushima, Takagi, and Muroyama 2006), with diffuser-type 1 developed having the diverging angle **f** fixed at 10° and that for the diffuser-type 2 at 6° respectively. The three flow acceleration structures area ratios **μ** defined as the outlet area/inlet area being 0.65, 1.64 and 1.45 for the nozzle 1, diffuser-type 1 and diffuser type 2 models respectively were achieved.

2.2. Laboratory experimental set-up

The study experimental measurements were carried out in a transparent-walled flume in the Hydraulic Engineering Research Laboratory of the Chair of Hydraulics Engineering and Hydraulic at TU Darmstadt. The flume has a measurement section of 15 m long x 0.9 m wide x 1.0 m high with an effective usable height of 0.8 m. The flume usable internal cross-sectional profile has a width of 2 m and height of 0.8 m and can accommodate maximum flow of 450 l/s. In this investigation, a partition wall was installed and a width of 0.9 m was used for this study. The flume wall is covered with acrylic glass that allows direct visualization of the flow dynamics. The system was constructed with a single transmission mechanism and wholly submerged in the flume flow as the generator is meant for under-water operation. The schematic illustration of the experimental setup is as shown in Figure 3.

The flow of water into the flume was regulated using the magnetic induction flow-meter having a volume flow standard error of ± 0.5% (MID- Magnetisch-induktiver Durchflussmesser, Endress+Hauser, Germany). The approach velocity in the flume was measured on the upstream section using Acoustic Doppler Velocimeter-ADV, Vectrino Plus (Nortek, USA) for 120 secs intervals at 25 hz sampling rate and ±0.30 m/s nominal velocity range. The Vectrino Plus device was positioned at the center of the flume with respect to the width. The Vectrino probes were positioned at a depth of 0.05 m from the bottom of the flume for the initial measurements and adjusted at 5 cm intervals in the Z-direction to record the flow velocity. The inflow into the flume was regulated using the gate-valve. The flow was adjusted from 90 l/s ± 0.5% which was the least flow required for the rotor rotation to occur. The flow was adjusted at intervals of 10 l/s ± 0.5% until the maximum flow of 150 l/s ± 0.5% which could be sustained in the flume was achieved. The corresponding flow velocities at the varied flow rates were measured and automatically recorded using the Vectrino Plus data acquisition software. The rotational speed of the rotor was initially measured using the VOLTCRAFT DT-10 L Tachometer having a measuring range of 2–99,999 rpm or REV: 1–99,999, an accuracy of ± (0.05%+ 1 digit) and measuring distance of 5–50 cm. When the rotor was installed inside the diffuser-type model, it was challenging to directly measure the rotation of the rotor using the Tachometer. Therefore, the frequency generated was measured using VOLTCRAFT VC281 TRMS Multimeter Digital CAT III 600 V having a basic accuracy of (±0.9%), voltage measurement range for both the DC and AC is 0.1 mV-600 V. The meter also has an AC frequency range of 45 hz-400 hz. The frequency value obtained for each test was converted to rotation per minute using the appropriate conversion formular. The voltage produced by the generator was also measured using the digital multimeter device. The rectification of the AC voltage produced was done

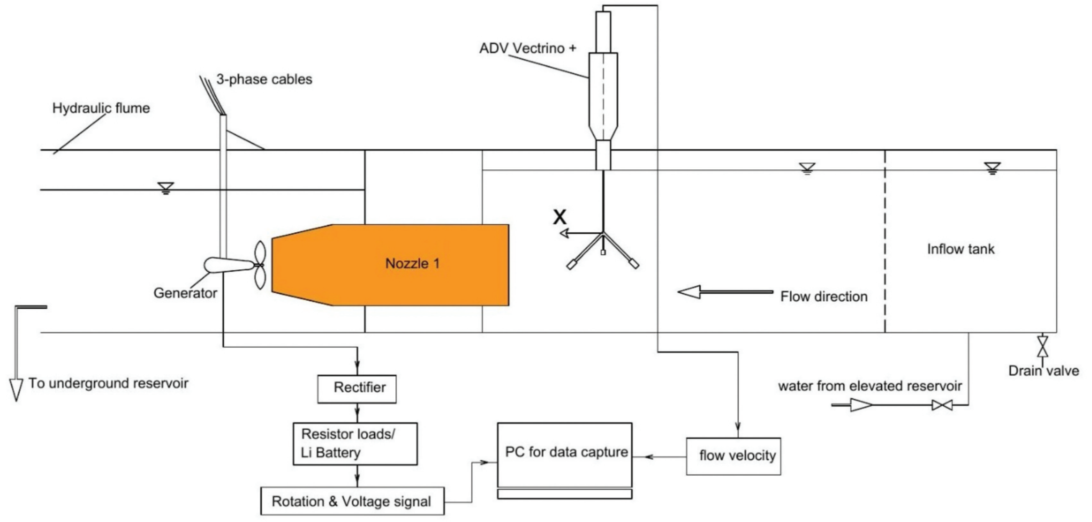

Figure 3. Schematic flume laboratory experimental setup layout.

using the electronic board constructed in the lab. A total of eleven resistors with 8 Ω resistance connected in parallel and could be switched on singly or in combination for the desired test load for the measurement process. Similarly, a lithium battery was used in charging mode when the resistors were not used as loads.

2.3. Dammed vs overflow condition using augmentation structures

In dammed condition, the inflow was blocked using the supporting structure of the set-up such that no/minimal space was available for the flow to bypass the turbine structure set-up (Figure 4a). Vortex formed at the inlet of the cylindrical nozzle (Figure 4a) during the initial tests of flowrates below 120 l/s, however, this phenomenon ceased with the increased flowrate in the flume that resulted to a rise in the water level at the inlet point of the nozzle. In the overflow condition, an opening was created such that flow over and besides the nozzle was realized as seen in (Figure 4b). However, this condition does not represent a complete overflow since the turbine support structures still obstructed the flow of water thereby creating some damming effect behind the inlet of the nozzle. Only nozzle 1 was tested in both dammed and overflow conditions. In the subsequent experiments, the tests were performed in the presumable overflow condition.

3. Results and discussion

3.1. Background

The chosen metrics for the comparison of the rotor hydrodynamic performance based on the use of the four varied hollow structures and conditions are the output power produced that was measured in voltage and the rotational speed of the rotor in both unloaded and loaded conditions For each hollow structure used, the experiments were conducted at least two times and the consistency of the results ascertained. The uncertainties in the measurement data was determined by calculating the standard deviation and the standard error of

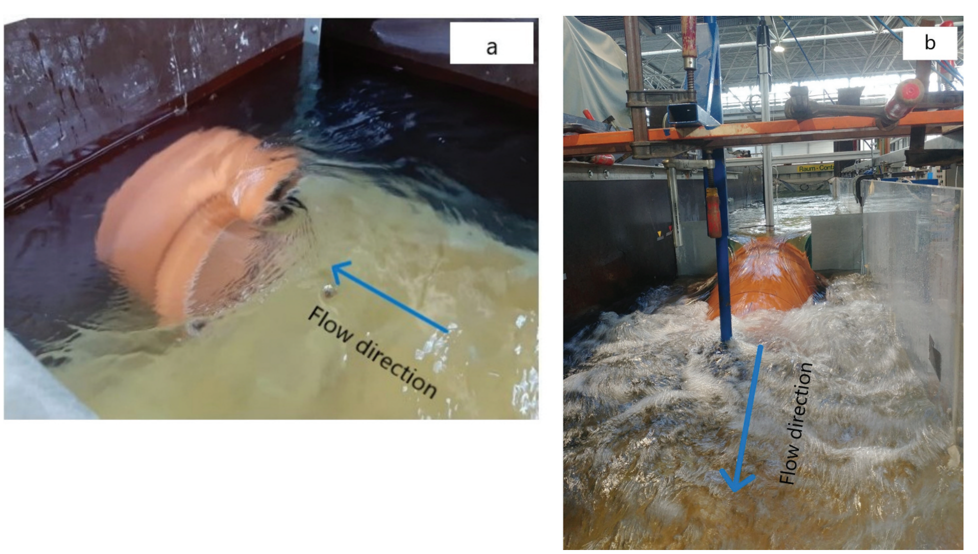

Figure 4. (a)Laboratory dammed condition, (b) Laboratory over-flow condition.

the measurements. The findings are reported as the mean ± the standard error. A sample calculated uncertainty is presented in Table 4.

The four varied hollow augmentation structures selected aided in achieving pressure recovery at the exit especially the use of diffusers which enhances the static pressure from the inlet to the outlet. The use of nozzle on the contrary decreases the pressure along its length. The structures also improved the flow direction capability. This enhances higher flow-directing efficiency leading to higher flux. Similarly, the use of nozzles helps in accelerating the fluid flow, resulting in high exit velocities. However, the diffusers decelerate flow, resulting in lower exit velocities. The different shape therefore leads to velocity profiles that affects the overall performance based on their configurations (Joshy and Sreejith 2021).

3.2. Flow velocity

The use of the flow acceleration structures showed an improvement in the flow velocity as the inflow approached the diffuser/nozzle inlet. In this experiment, the mean approach velocity profiles upstream of the shrouds were measured and recorded using the ADV Vectrino Plus (Nortek, USA). For the maximum inflow rate of 150 l/s that could be sustained by the section of the flume available for this experiment, the corresponding approach flow velocity was found to be averagely 0.247 ± 0.002 m/s. The structures therefore enhanced the kinetic flow of the inflow (see Figure 5(a,b)) thereby increasing the power extraction ability of the shrouded rotor even at low approach velocities. The flow velocity enhancement reaching the rotor was further computed to assess the predictive performance of the experimental investigation. This was determined using the equation of continuity (equation *3.1*) shown below, where A_1 and A_2 are the cross-sectional areas of the shroud at inlet and at throat (where the rotor is positioned) and V_1 & V_2 are the corresponding velocities at the inlet and at the throat respectively.

$$A_1V_1 = A_2V_2 \qquad (2)$$

In this experimental study, the free stream (approach) velocity of flow ranged between 0.153 ± 0.005 – 0.247 ± 0.002 m/s for the flow that could be sustained within the test section of the flume. The use of the diffusers or nozzles helps in the concentration of the flows toward the turbine rotor thereby enhancing the flow velocity and power production (Anbarsooz, Mazloum, and Moghadam 2020; Joshy and Sreejith 2021). The flow accelerators improve the approach flow velocities as depicted in Figure 5a which is further enhanced toward the turbine.

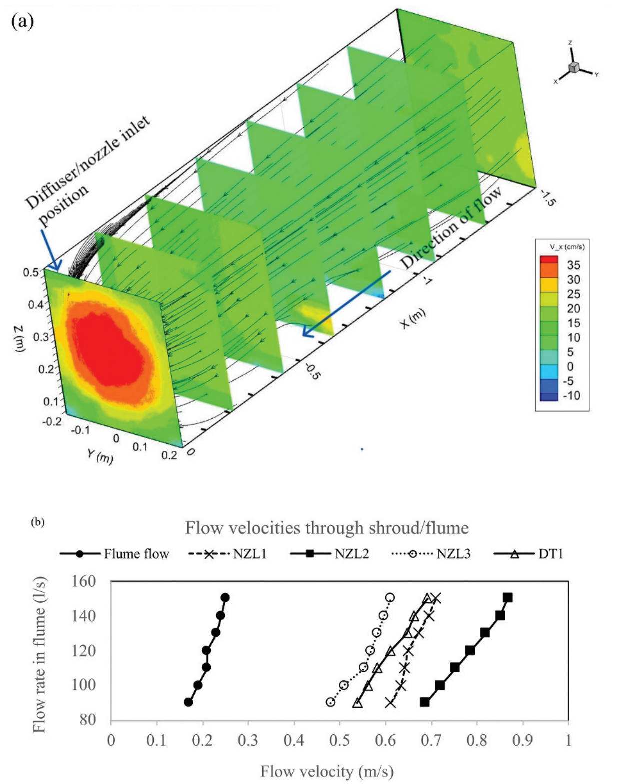

Figure 5. (a) Tecplot flow velocity profile in the flume; (b)Flow velocity comparison with acceleration devices.

3.3. Geometry profiles performance

This study focused mainly on the experimental design and construction of a functional micro-hydrokinetic technology prototype for a possible application in shallow tropical and equatorial rivers. The mechanical shaft power was not determined since the torque measurement devices were not available. However, the electrical power output which was the main parameter for evaluating the performance of the device was determined from the experimental data using the appropriate formula. Additionally, no specific measurements that would lead to the determination of the component efficiency was performed.

Nozzle 1 was operated in both the damming and overflow conditions. The two operation conditions had varied influence on the output performance of nozzle 1. In similar manner, the performances of diffuser-type 1, nozzle 2 (when diffuser-type 1 was used in reverse orientation) and nozzle 3 were experimentally investigated only in overflow condition to provide an overview of what is expected in natural site conditions. For future development of the pilot project, no physical damming

Table 4. Uncertainty analysis for the nozzle 2 experimental data.

RPM	AC (V)	AC (V)	AC_avg	standard error (α)	DC (V)	DC (V)	DC_avg	standard error (α)
735	7.268	6.914	7.091	0.177	7.913	8.105	8.009	0.096
795	7.673	7.351	7.512	0.161	8.387	8.507	8.447	0.06
840	8.292	7.812	8.052	0.24	9.087	8.717	8.902	0.185
870	8.417	8.393	8.405	0.012	9.216	9.208	9.212	0.004
885	8.625	8.401	8.513	0.112	9.787	9.701	9.744	0.043
915	8.621	8.495	8.558	0.063	10.015	9.817	9.916	0.099
930	8.927	8.681	8.804	0.123	9.935	10.141	10.038	0.103

of the river is to be undertaken as the available kinetic flow of the river is to be extracted in its natural state.

Figure 6 presents the performance comparison of nozzle 1 in both overflow and damming conditions. Considering nozzle 1, it can be seen that there is an excellent performance in the damming condition compared to overflow condition. With an 8 Ω load, nozzle 1 produced 13.248 ± 0.123 V DC and 11.395 ± 0.008 V AC in dammed condition compared to 8.111 ± 0.107 V DC and 7.116 ± 0.098 V AC when operated in over flow condition. This is attributed to the fact that the upstream water level rose slightly due to the complete blockage of flow using the support structures (see heading 2.3) thereby creating a slight potential head that enhanced the performance of the rotor (Kirke 2019; McAdam, Houlsby, and Oldfield 2013) as the flow passed through the nozzle to the HKT device.

The voltage characteristic curve against rotational speed of the rotor for the diffuser-type 1 in Figure 7 resulted in a maximum voltage production of 7.147 ± 0.144 V AC and 8.053 ± 0.082 V DC respectively in the overflow condition. The use of the diffuser was intended to accelerate the approach flow velocity toward the rotor at the inlet section. This occurs by generating a low pressure region through the vortex formation at the outlet region thereby drawing more flow through the inlet of the diffuser (Ohya and Karasudani 2010). In contrast, the diffuser-type 1 performed extremely well when used in reverse orientation as *nozzle 2* (see Figure 2b). The voltage characteristic curve against the rotor rotational speed for nozzle 2 in comparison to the same structure when used as a diffuser improved the performance from 8.053 ± 0.082 V DC and 7.145 ± 0.053 V AC to 10.038 ± 0.103 V DC and 8.804 ± 0.123 V AC respectively as shown in Figure 8 when subjected to same flow velocity in the flume. This enhanced performance is attributed to the gradual change in the cross-sectional area of the nozzle-diffuser augmentation that significantly improved the incoming flow velocity that hits the turbine blades due to the effect of the angled geometry of the combination (Joshy and Sreejith 2021). Except for nozzle 1 which was used in both dammed and overflow conditions, a comparison performance of the remaining shrouds in dammed condition was not done in the laboratory as the results were expected to be better than in the supposed overflow condition. Considering that damming raised the water head behind the inflow section of the shroud, this resulted in an excellent performance. Similarly, the main consideration in the assessment of the performance of the shrouds was to identify a suitable structure that would be adopted in the planned field experiments where damming of the river is not planned.

Nozzle 3 (see Figure 2d) had a reduction in inlet diameter (D) compared to nozzle 2 and an increase in length L (see Figure 2(b,d)). The test was conducted using this flow accelerator only as a nozzle and the use as a diffuser was not considered since diffuser-type 1 already showed a lower performance compared to when used as a nozzle in the reverse orientation. From the voltage characteristic curve against rotor

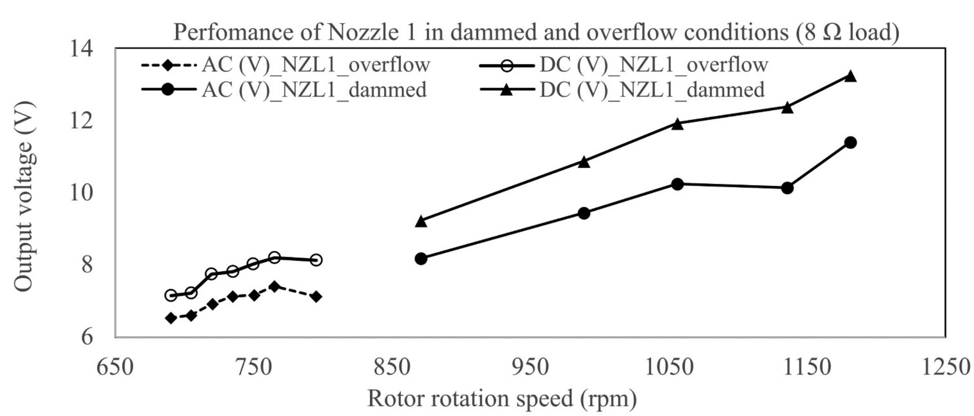

Figure 6. Nozzle 1 performance comparison in overflow and dammed condition.

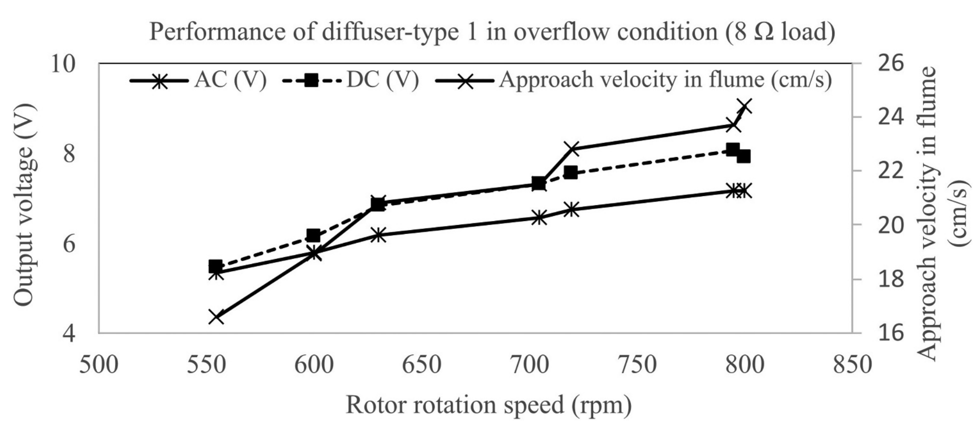

Figure 7. Performance of Diffuser_Type 1 in overflow condition.

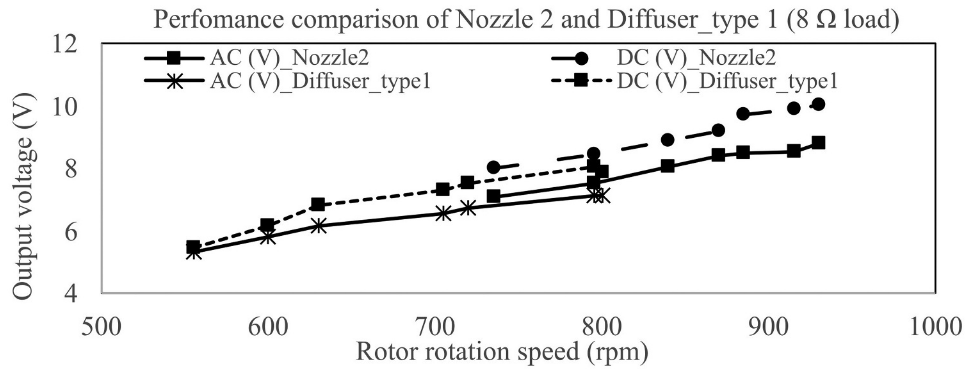

Figure 8. Performance comparison of nozzle 2 and Diffuser_Type 1 in overflow condition.

rotational speed as shown in Figure 9, the performance of nozzle 3 realized a voltage value of 8.523 ± 0.009 V DC and 7.548 ± 0.014 V AC respectively with the turbine rotation speed of 795 rpm at a flow velocity of 0.25 m/s in the flume. In comparison to the dimensions of nozzle 2, the flow acceleration is significantly influenced by the inlet diameter and not the length of the nozzle as can be established using the continuity equation (see equation *3.1*). The performance characteristic curves for the nozzle 3 in overflow condition and bare turbine are compared in Figure 10. Bare turbine performed exceptionally poor in comparison to when ducted in nozzle 3.

The voltage characteristic curve against rotational speed presented in Figure 11 outlines the performance comparisons of the various shrouds used. From the performance curve the *nozzle 2* produced a promising performance. The rotational speed of the rotor increased significantly and this resulted in a higher voltage generation. Nozzle 2 had a larger inlet diameter than the rest of the other shrouds compared and having a constant throat diameter of 275 mm where the rotor was positioned. As a result, the gradual change in the cross-sectional area of nozzle increased the flow velocity hitting the rotor blade and a subsequent reduction in pressure thereby enhancing the rotational speed of the rotor and electrical energy conversion of the generator. In comparison, since nozzle 2 has a larger diameter compared to the other shrouds, by applying the equation of continuity, this results to a higher flow velocity at the point where the rotor is positioned, thus an increased performance of nozzle 2.

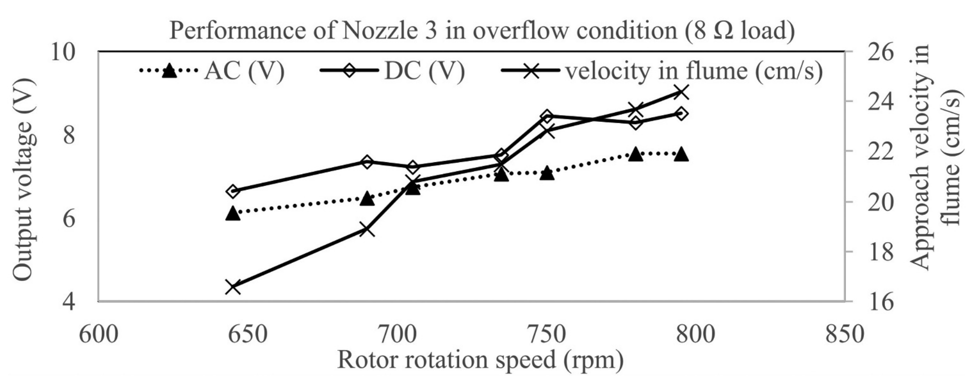

Figure 9. Performance of nozzle 3 in overflow condition.

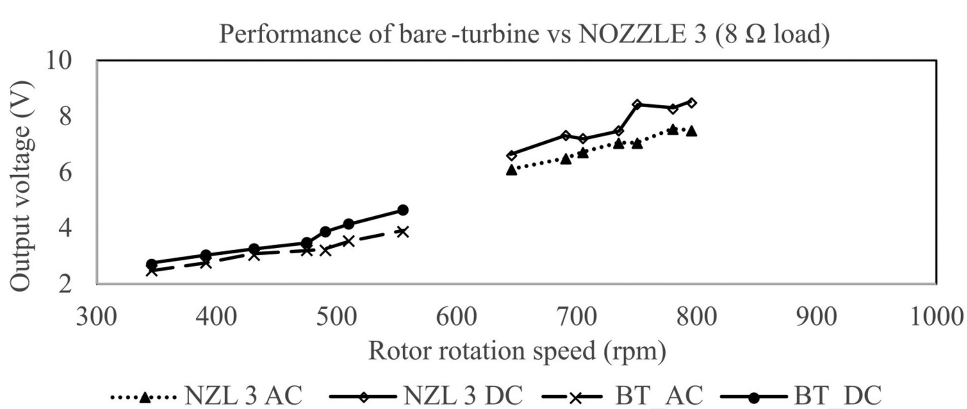

Figure 10. Comparison of performance of bare turbine and nozzle 3 in overflow condition.

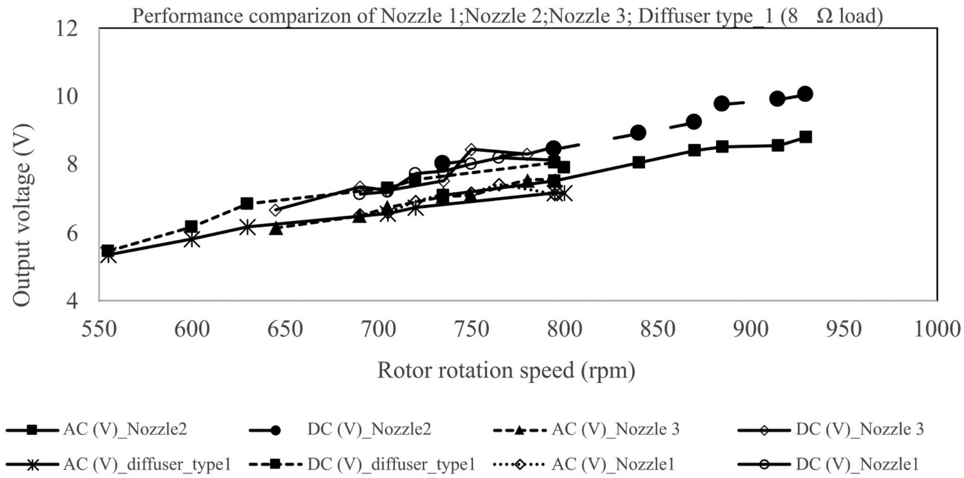

Figure 11. The comparison performance of all the flow accelerating devices (nozzle 1; nozzle 2; nozzle 3 and diffuser-type 1) in overflow condition.

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 (Kirke 2019, 2020). Various state of the art hydrokinetic turbines industrially manufactured have been intensively described and their performances compared (Kirke 2020). In comparison, performance of the prototype described in this article is way far below the industrially manufactured turbines highlighted in Table 1. This work mainly focused on the possible utilization of the considered e-waste components for developing energy conversion systems for the generation of small amount of energy for use in developing rural areas that have no grid connection. In this case, despite the high rotational speeds measured, the performance of the generator is found to be low. This could suggest that the turbine component is not suitable for use as energy conversion system as its efficiency seems to be low. Comparing the performance with the study conducted in (Tan, Kirke, and Anyi 2021), the decommissioned boat motor is a high speed component that requires high rotations for its normal operation as a motor but when used as a generator it is found to be unsuitable for use as energy converter.

3.4. Evaluation criteria

3.4.1. Cost comparison with diesel generator

In order to establish the viability of the system in consideration, feasibility study need to be conducted with emphasis on the socio-economic benefits of the proposed technology for the rural community. The use of diesel-powered generators provide the most popular means of electrification of rural areas having been viewed as a cheaper and most available option for rural off-grid power back-up (Nasab, Navid, and Bakhtiaryfard 2021). However, with the current increase of prices of the petroleum products and transportation challenges of the fuel to remote rural areas renders this option to be unsustainable in the long run. The generators are noisy and also require regular maintenance (Azizul, Mohd Amin, and Razlan, 2019; Lau and Tan 2021; Tan, Kirke, and Anyi 2021). The diesel-powered generators adds to the environmental degradation due to the green-house gas emission that influences the global warming effects (Vermaak, Kusakana, and Koko 2014).

The socio-economic evaluation requirements such as selection of suitable off-grid site, determination of power demand, definition of microgrid components, acquisition of hydro resources and feasibility analysis and financial viability of the technology versus use of diesel generator shall be determined using HOMER Pro simulation software as proposed and outlined in literature (Koko 2014; Koko, Kusakana, and Vermaak 2013; Nasab, Navid, and Bakhtiaryfard 2021) for the planned field trials. It is anticipated that with the adoption of the technology for lighting purposes, the dependence on kerosene for lighting for instance will be eliminated and thus improves the wellbeing of the users. The potential of other low energy use services like mobile and solar lamps charging can be of economic benefits to the community (Koko 2014; Kusakana 2014).

3.5. Challenges associated with HKT technology

For practical application of the prototype and its widespread use, there are unforeseen challenges likely to be experienced. The problem of debris accumulation resulting from floating materials is of great concern as these can lead to damages of the blades and reduced flow through the turbine system as most tropical rivers flow through the jungles thus collecting lots of logs, leaves and other related jungle trash (Anyi, Kirke, and Ali 2010). During flash floods, the installed turbines can be swept away rendering the villages to power cutoff. The electrical conversion components such as the generators are not available for free and thus has a monetary value. The production workshop, labor force, regulatory permits and other amenities require financial input and as such the inadequate initial capital is likely to hamper the scalability of the prototype. Lack of political good will in terms of policy that tend to reserve a great favor on the fossil fuels as the authorities willfully provide subsidy for fossil fuels (Ang et al. 2022).

4. Conclusion

This article has outlined a laboratory experimental investigation to demonstrate the performance of a low-cost hydrokinetic turbine technology developed from e-waste and off-the-shelf local materials to enhance the access to electricity in remote off-grid rural areas for an improved livelihood.

An HKT was developed using a decommissioned boat motor and operated as a turbine-generator combination. Flow acceleration structures namely diffusers and nozzles were developed from materials that are available from the local hardware stores and their performances investigated. From the performance comparisons of the augmentation structures, nozzle 2 produced an excellent performance (10.038 ± 0.103 V DC and 8.804 ± 0.123 V AC respectively), an equivalence of 12.595 W or 0.302 kWh per day. Nozzle 2 is therefore best suited for adoption for the field tests.

From the power generation performance of the HKT with varied augmentation structures as outlined in Section 3.3, and the limitations of imported state-of-the-art HKT described in Section 1.2, the following conclusions can be derived:

- In rural areas where small amount of electricity is sufficient to enhance the socio-economic wellbeing of the society, the power produced using a locally developed low-cost HKT technology in upscaled version can be sufficient for some low energy demand activities.
- The provision of technical expertise empowerment to the local community would be necessary to enhance the sustainability of the technology, thereby lowering its operation and maintenance costs. This can be achieved through education and training of selected members of the local community the hands-on skills requirement of the operations and maintenance of the system.
- There is need for a comprehensive hydro resource investigation of the sites of interest to determine the suitability and adaptability of the technology since performance of the hydrokinetic systems vary with location.
- Theoretically compared to the small diesel-generators, the generators are the cheapest to buy but with the uncertainties in the prices of fossil fuels, generators may become expensive over their operating life compared to the HKT that can operate 24 hours.
- The use of HKT is environmental friendly as compared to the total harmful emissions realized from several units of diesel-generators over their operating life (Mohamad, Mohd Amin, and Razlan 2019).

Further field test investigation of the prototype is planned to determine its performance based on the prevailing field conditions. This will provide a basis for a pilot project being considered for a selected off-grid rural site.

Acknowledgements

The corresponding author acknowledges the financial support by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) and the Open Access Publishing Fund of the Technical University of Darmstadt for the Article Processing Charges (APC). He also acknowledges his employer, Masinde Muliro University of Science and Technology, for granting him the study leave to undertake his doctoral research at TU Darmstadt. Many thanks to the colleagues in the Chair of Hydraulic Engineering and Hydraulics for the technical and administrative supports. Words of appreciation to Katholischer Akademischer Ausländer-Dienst (KAAD) for the sustenance scholarship at TU Darmstadt.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This research received no external funding. The APC was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) and the Open Access Publishing Fund of the Technical University of Darmstadt.

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Data availability statement

Additional supplementary data that support the findings of this study are available from the corresponding author, WA, upon reasonable request. The data presented in this study are sufficient for better understanding of the study outcome.

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