Design and construction of an off-grid gravitational vortex hydropower plant: A case study in rural Peru

Vladimir J. Alzamora Guzmán, Julie A. Glasscock, Ferris Whitehouse

Energy Research Group, Kadagaya Research Centre for Appropriate Technology, Miricharo, Chanchamayo, Junin, Peru

A R T I C L E   I N F O

Keywords:
Gravitational vortex
Micro-hydropower plant
Developing countries
Low-head hydropower
Turbine

A B S T R A C T

Low-head hydroelectric technology is allowing the expansion of distributed power systems into isolated regions that are difficult to connect to the grid. Such technology can provide renewable energy resources to a wider population, especially in developing countries. Here, we evaluate a 10-kW-scale gravitational vortex hydropower (GVHP) system constructed on a river in rural Peru. Detailed specifications of the design, construction, and initial testing are given, along with a basic economic evaluation. We critically compare the GVHP technology to mature low-head hydropower technologies. The GVHP technology is suitable for operation at a head as little as 1 m with a minimum flow rate of 0.5 m³/s. We demonstrated that the GVHP infrastructure could be constructed with a high level of manual labor, with materials and technologies available in a developing country. The relatively small investment cost and short payback time make it an interesting option for small rural communities where connection to the grid is not favorable, or where the simplicity of the design outweighs the need for high efficiency. Labor was the main cost (despite inexpensive labor in Peru). Considering the challenging high-torque operating conditions, power transmission from the turbine to the generator is a major limitation of this system.

Introduction

The global energy demand is increasing by an average of 1% every year, where electricity demand is increasing even faster [1]. Renewable energy sources still account for less than 20% of the total final energy consumption [2]. South America has the potential to provide these energy needs with renewable sources, particularly hydroelectric power. Brazil, Ecuador, and Peru are among the top nine producers of hydro-power globally, where the vast majority is large-scale hydropower plants; Peru generates around 34% of its electricity with hydropower (2015 estimate) [3]. There is a global trend towards off-grid distributed energy systems, which are particularly suitable for rural communities in developing countries where extensions of the grid are economically unattractive due to the geographical isolation and low income of the potential consumers [4]. Such distributed energy systems save the cost of running transmission lines from the grid and in many cases the technology is simple enough to be installed and maintained by the local community. Most populations without reliable access to energy are in poor remote rural areas and electrification provides valuable economic and social development for such regions [5].

Global installation of hydropower is accelerating annually, although most new developments are large-scale projects. Many of the unexploited sites for further hydropower development are thought to be suitable for small hydropower (SHP; less than 10 MW) and micro-hydro systems (less than 100 kW) [6]. In particular, low-head sites (from 0.8 m up to 2 m) are currently an under-exploited niche for power generation [7,8] and avoid many of the environmental concerns associated with traditional MW-scale hydroelectric plants, such as destruction of river ecosystems by the installation of large dams. Avoiding dams also limits the social impacts of reducing water access to downstream users, which is particularly important in economies that rely heavily on agriculture, such as that of Peru. As the generated power depends on both the head (potential energy) and the flow, high-head sites are able to operate at quite low flows, while low-head sites require high-flow conditions [9]. Such a system is thought to be highly suitable for isolated rural areas and is already being implemented in Nepal [10,11]. Water volumes in the range of 0.5–20 m³/s are suitable for yielding 17–3300 MWh/y [12].

The gravitational vortex hydropower (GVHP) system exploits the energy contained in a vortex flow. The water passes through a straight inlet channel into a spiral-shaped or conical tank where a strong vortex is induced. The water exits through a central outlet at the bottom of the tank and is returned to the river. A vertical-axis turbine is placed in the center of the water vortex and rotates coaxially with it to harness the...
kinetic energy. A major advantage of the GVHP (and other low-head technology) compared to large-scale hydropower is the reduced environmental impact, particularly related to the preservation of wildlife habitat and the ability for fish to migrate safely in both directions (without fish ladders) due to the low speed of the turbine and no large dams. In addition, the GVHP effectively aerates the waterway, revitalizing water courses, avoiding the stagnant water created by MW-scale hydroelectric dams that emits significant amounts of greenhouse gases (especially problematic in tropical regions [13]). For these reasons, this technology is being evaluated for generating power from existing water infrastructures (where vortices often exist in pumping stations) and wastewater streams [14,15], e.g., municipal drainage in cities in India [16], with the added benefits of automatic solids separation and aeration to improve water quality. Various GVHP systems have recently been commercialized [12,17–19] and patented [20]. A few research groups are investigating similar systems and working to optimize the tank geometry and turbine design to increase the efficiency [10,11,21–23]. Computational modelling of the vortex formation has been undertaken [24,25], along with experimental studies [26]. Some basic economic feasibility studies have been undertaken, which show competitive results compared to the price per watt of alternative renewable and non-renewable energy sources in developing countries [16,27,28].

Although the GVHP system seems to be a promising low-head technology for application in developing countries, case studies of full-scale systems operating under real conditions are lacking. Most studies evaluating the efficiency of the GVHP technology have investigated laboratory scale tanks and turbines, while only a few small-scale pilot plants have been built (e.g., a 1.6 kW system [28]). While several companies are investigating 10–20 kW systems, they have not openly published performance metrics. For example, Zotlöterer claim a very high turbine efficiency of 80% [17], which is significantly higher than the values generally reported in the scientific literature [11,26]. Hence, a critical analysis of the upscaling of this technology is required.

This case study reports the design, modelling, construction, and testing of a 10 kW-scale GVHP plant in rural Peru. We consider the entire system, including the geometry of the channels, tank, and other physical infrastructure, the mechanical components (e.g., turbine and gearbox), and the electrical system (generator and regulation system). In addition, the suitability of the GVHP technology as a distributed micro-hydro option for rural developing communities is evaluated considering a basic economic analysis. Furthermore, the system is critically compared to existing low-head hydropower technologies. We provide detailed information that is expected to be useful for replicating and upscaling this technology, and propose strategies for reducing the construction costs and increasing the durability of the system.

Site location and characteristics

The GVHP constructed in this study is located on the Pichanaki River in Chanchamayo, Junin, Peru. The plant is fully owned by Kadagaya and was designed to provide energy for the research center campus (future housing for about forty people, as well energy for laboratories and workshops). This is a tropical region that receives high rainfall, over 2000 mm annually, with a minimum of 70 mm per month during the dry season [29]. The river flows strongly all year round and is a reliable source of water for generating energy. In the wet season there is a risk of landslides and the river being loaded with mud, trees and other debris. Hence, the GVHP system is located inland from the river (with entrance and exit channels to facilitate the flow of water) to ensure that the infrastructure is safe from flooding. The natural slope of the river at the available site is around 1.5% (15 cm per 10 m) which can achieve a head of around 1 m over the length of the total infrastructure. Surveying of the levels of the site was performed using a water level float, and at least three measurements at each point were taken to calculate average values. Care was taken to choose appropriate measurement sites and avoid rocks in order to accurately determine the river bed level. The minimum velocity (in the dry season) is around 0.5 m s\(^{-1}\). These conditions are suitable to theoretically generate between 5 and 10 kW of power [17]. We refer to our GVHP as a 10-kW-scale system (although maximum output power has not yet been demonstrated), simply to define the scale and differentiate it from e.g., a 1-kW-scale or 100-kW-scale system.

System design

Dam and dyke

Fig. 1 is a schematic diagram showing an overview of the site, where the inland location of the GVHP is shown, along with the dam and dyke, inlet channel, tank, and outlet channel. A dyke was constructed to dam a small portion along the riverbank, where the capture area was limited to that shown in (a) and did not continue across the entire river. This served two functions; firstly to increase the capture area and funnel water into the inlet channel, and secondly a small increase in head is gained. The dyke was constructed using gabions filled with smooth river stones and coated with a concrete layer. The dyke has a width of 2 m, height of 1 m, and a length around 30 m and was located at a maximum distance of 8 m from the riverbank. This geometry provides a theoretical cross-sectional flow rate of 1.4 m\(^3\)/s considering the slowest
speed of the river (8 m × 0.35 m minimum water depth in the dry season). A higher dyke allows an increased capture volume, which is advantageous in the dry season to harvest more water, and hence energy. However, during initial testing in the wet season we observed that the original dyke height of 1.5 m allowed too much water to enter the inlet channel (when the river level was high), applying too much pressure on the inlet gate and resulting in an excessive turbine speed. Hence, the dyke was lowered to 1 m in height, which allows the swollen river to flow over the dyke and protect the system from flooding.

There are two gates at the entry to the inlet channel. The first controls the water entering the inlet channel from the dam. The second gate is at right angles to the first gate (and flow of the river) and allows the water to flow directly back into the river when the main gate is closed for maintenance of the system. This gate can also be used to help regulate the flow of water into the inlet channel. A diagonal debris screen was installed diagonal to these gates (parallel to the river bank), to prevent large logs and rocks from entering the inlet channel and damaging the infrastructure.

**Channel and tank**

The geometry of the channel and tank were optimized with respect to the head, velocity, vortex geometry, and theoretical power output. A starting tank diameter around 5 m was used as a reference [30]. The channel lengths were calculated to give a total head of 1.6 m from inlet to outlet, which combined with the slope of the river (1.5%) gave a total required length of the channel of around 100 m. The channel has a trapezoidal cross section to optimize the use of cement while achieving the desired volumetric flow. The channel height extended another 30 cm above the designed head of ~1.3 m in order to accommodate overflow of water during the rainy season. An overflow channel located 10 m before the entrance to the tank removes excess water in order to prevent flooding of the tank in the wet season.

**Turbine**

Turbines suitable for low-head hydropower applications are different from the reaction turbines commonly used in conventional hydropower plants (such as, Francis, propeller, and Kaplan designs) [31]. Low-head/high-flow systems such as the GVHP generally use submerged impulse-type turbines, such as cross-flow turbines. Here, a vertical axis cross-flow-type impulse turbine was used; this design was selected as it has a simple structure that can be constructed using relatively basic tools in rural communities [5]. A cross-sectional diagram of the turbine position in the tank with respect to the water vortex is shown in Fig. 3. The initial testing described in this paper was performed using a turbine with a diameter of 1.15 m. Sixteen turbine blades with a width of 32 cm were mounted equidistantly around the circumference, where the blades were fixed at the top by a wooden disc and at the bottom by a metal ring with reinforcement spokes. The turbine geometry was selected based on designs presented in the literature (as reviewed by Wack and Riedelbauch [32]) and used in commercial systems [17]. The turbine diameter was designed considering the size of the exit hole in the floor of the tank, which determines the size of the air core of the vortex. The water accelerates as it travels to the center of the vortex and hence, the rotational velocity is higher closer to the air core (for irrotational fluids). To maximize the average velocity of the water in contact with the turbine blades, it is better to have contact with only the faster moving water at the center, while ensuring sufficient contact area to provide the desired torque. The diameter of the turbine was designed to be about 10 cm larger than the diameter of the exit hole (1.05 m).

In GVHP systems, it has been shown that the velocity of the turbine depends on its vertical position within the vortex core [20]. Dhakal et al. observed maximum power extraction at a runner position of 65–75% of the total height of the vortex [11], while Power et al. [26] found an optimal position closer to the bottom of the tank (35% of the overall tank height). The energy collected by the turbine is dependent on the area of the water vortex intersected by the turbine blades and the water velocity. As the velocity varies across the water cross section, the efficiency is dependent on the turbine blade geometry, size, and placement within the vortex. The tangential velocity is highest closest to the air core, so there is a trade-off between having a large enough blade size to capture sufficient energy, without excessively increasing the radius of the turbine and decreasing its rotational speed. Turbine optimization is required for all hydroelectric systems in order to extract the maximum energy from the particular water source. As the GVHP technology is relatively immature, this optimization is still being performed by our group and several others, and was not a focus of the present study. Based on these previous studies, the length of our turbine was 90 cm and was placed 7 cm from the bottom of the tank. The blades had a radius of curvature of 70 cm, where the concave sides were impacted by the water flow. The angle between the tangent of the turbine and the outside tangent of the turbine blades was 16°. The central axle of the turbine was fixed by two bearings, one mounted on the bottom floor of the tank (the base of the hole) and another connecting the turbine to the gearbox. The lower bearing was specially designed to operate submerged in water.

Initial testing was performed using a mechanical gearbox with a gearing ratio of 1:29. This gearing ratio was chosen based on initial measurements of the angular velocity (rpm) of the turbine and the requirements of the 4-pole alternator (which needs an input of 1800 rpm). As the goal of the study was to use easily available technology, we chose a gearbox that was the most commercial in the market (e.g., for truck engines). The gearbox was operated in the vertical direction with a modified lubrication system to ensure adequate oil supply to all gears. A vent hole was inserted in the gearbox casing to prevent pressure overload from the expansion of the oil during operation. The turbine operated at around 70–80 revolutions per minute (rpm) with no load, hence the speed of the axle exiting the gearbox (and entering the

![Fig. 2. Schematic diagrams of cross-sections of the vortex tank. (a) Overview of the water levels and the vortex surface. (b) Dimensions of the various parts of the rotation tank where D is the tank diameter, T is the tank depth, a is the hole diameter, E_1 is the width of the exit slot, E_2 is the height of the exit slot, and t_1 and t_2 are the thicknesses of the upper and lower concrete floors.](image)
alternator) was around 1800 rpm. As the turbine speed was quite slow, it was measured by marking a reference point on the turbine rim, and the time to complete 30 revolutions was measured. At least five measurements for each condition were averaged. These values were confirmed using video footage of the turbine running.

Electrical system

A three-phase system was chosen as it is more efficient in production and transport, and a simpler generator is required than for single-phase production. A three-phase AC brushless alternator (10 kW, model FLD162E, Jiangsu Farrand Alternator Technology Co., Ltd., China) was used. This alternator has a built-in automatic voltage regulator (AVR) that controls the output voltage to 400 V, where the output frequency is 50–60 Hz. The alternator has a single bearing and hence, the alignment of the alternator and gearbox needs to be very precise to ensure that the system does not vibrate excessively during operation. Parallel coupling discs were used to attach the turbine to the gearbox and the gearbox to the alternator.

There are two main methods for controlling the velocity of the generator (and hence, output frequency) in hydroelectric systems; regulating the water input or the load. While high-head (e.g., Pelton) systems with narrow penstock tubes can easily control the water volume using mechanical governors, electronic control is more appropriate for the GVHP system; in addition it is more simple, less expensive, requires less maintenance, and allows the system to respond faster to load requirements [33]. An effective way of regulating the electricity is via the use of a system to dissipate the excess energy via a dump load (so the system always operates under full load) to avoid fluctuations in the frequency from changes in the turbine rotation speed. This is most easily and commonly achieved by resistive heating of air or water. This waste energy can be used for space heating or for producing hot water. In our case, an electronic load controller (ELC) system was designed in-house to provide a dump load using water heaters. Three 2 kW heating elements were installed in the exit channel, which are automatically controlled to regulate the system to full load at all times. This allowed the rotation of the turbine to be regulated to achieve a stable output frequency around 50 Hz.

The electrical cables (5.26 mm² solid copper) were run around 500 m up the hill from the river to the campus. The cables were pulled through a conduit tube and then buried. Three single phases (220 V) were separated from the three-phase line to supply different buildings. Standard household electrical boards were used with 10 A breaker switches. An additional stabilizer was used to ensure that the source power was protected from current peaks.

Results

Channel and tank design

Fig. 4 shows schematic diagrams of top-views of the tank, defining the geometric variables and geometry used in this case study.
shows the geometric variables defined by Mulligan et al. [23], where the inlet channel width to the tank is restricted to give a width $b$ and $D_{eff}$ is the effective diameter of the tank. The initial selection of tank geometrical variables was based on this theoretical study and discussions with the authors. Previous modeling studies showed that this inlet restriction improved the flow properties in the tank, resulting in a stronger vortex, which should theoretically increase the power and efficiency of the system. However, during initial testing of the water flow in our tank with the geometry shown in Fig. 5(b), we observed that the flow rate was excessively reduced and the full output of the tank could not be achieved. Hence, the restriction was removed to give the geometry shown in Fig. 5(c). Such unexpected results highlight the need to testing full-scale GVHP systems in order to critically evaluate their performance for power production.

Upon completion of the cement infrastructure, the inlet gate was opened and water from the dyke was allowed to flow into the inlet channel and tank. The water filled to a head around 1 m and a stable vortex formation was observed in the tank. Videos of the vortex flow can be seen in the Supplementary Material. With an outlet hole diameter of 1.05 m we estimated an air core of around 75 cm. We estimated the volumetric flow rates in the inlet channel by measuring the surface velocity of the water by dropping a float at a specified point and timing its travel over a distance of 3 m. At least five measurements were made for each head condition. Flow rates of 1.0–1.3 m$^3$/s for heads of 1–1.35 m, respectively, were measured. These flow rates were much lower than we expected, resulting in power values of only 2–3 kW. With the turbine installed we observed similar flow behavior and calculated rpm values of 50–60 rpm under load. A photograph of the completed system used for the initial testing discussed here is shown in Fig. 6.

Power output

The maximum power obtained by our system under the conditions described in previous sections was around 3.3 kW (at a head of 1.35 m, turbine speed of 55 rpm, and flow rate of 1.35 m$^3$/s), which corresponded to a total system efficiency of around 17.5%, which is within the range of values (10–30%) most commonly reported for experimental and model systems to date [11,26]. Wiemann et al. [7] reviewed numerous emerging low-head technologies and concluded that the efficiency stated by manufacturers of GVHP systems is overly optimistic and estimated a more realistic value of around 35%. Changing the head in our system from 1.15 to 1.35 m resulted in an increase in flow rate from 1.07 to 1.35 m$^3$/s, respectively, and corresponding increase in turbine speed of 49–55 rpm, respectively. The maximum volumetric flow rate was 1.35 ± 0.1 m$^3$/s compared to the theoretical value of 1.4 m$^3$/s calculated from the geometry of the dam, which was attributed to the loss of some water through gaps in the dyke and the inconsistent water depth/uneven river bed in the dam as the calculation was based on average values. Fig. 7(a) compares our obtained system efficiency as a function of turbine speed with a 14.5 W experimental system [34]. A 1.6 kW pilot-scale system installed in Nepal showed much higher values (up to ~80%) [28], but these values have not yet been reproduced. Although our efficiency values increased slightly with increasing turbine speed, it is clear that the turbine characteristics were insufficient to achieve further efficiency increases. The Nepalese groups have invested much effort in optimizing the geometry and placement of their turbines, and have achieved significant increases in efficiency as a result. Hence, we are confident that further efforts to optimize our turbine for our specific tank geometry can achieve similar efficiency gains.

The system efficiency values were converted into a turbine efficiency assuming efficiency values of the alternator and transmission system of 90% and 85%, respectively. The losses in the transmission are due to friction losses from imperfect alignment of bearings. The turbine efficiency was plotted against the normalized flow rate ($Q/Q_{max}$) and compared to that claimed for a commercial GVHP system [17], along with competing low-head technologies (an overshot water wheel with a diameter of 3.6 m [35], and an Archimedes screw turbine system [36]). As noted earlier, the excellent performance claimed by the commercial manufacturer has not yet been reproduced by research groups, so these values must be considered unverified. A similar comparison of a wide range of low-head turbines has been reported previously [36]. We did not see the curve shape typical of such low-head systems, again attributed to an inappropriate turbine geometry. We believe that the cross-sectional area of our turbine intersecting the water profile was simply too small to harvest sufficient energy from the vortex. Further tests are being performed with a larger turbine (wider diameter and larger blade area) and larger hole in the tank floor in an attempt to increase the power output.
Evaluation of the GVHP technology

Cost analysis

Wiemann et al. predicted an installation cost of a GVHP system of around 6000 EUR/kW [7], while the Zotlötter company quotes a higher cost of 10,000 EUR/kW [37], which translates to a total cost of around 69,000–115,000 USD for a 10 kW system (assuming 1.15 USD = 1 EUR). Similarly, a European comparison of various low-head technologies predicted a cost of 2500–4800 EUR/kW (around 42,000 USD for a 10 kW system) [36]. Installation of such a system in a developing country such as Peru is significantly less expensive, due to lower costs of labor and minimal planning and authorization requirements (the latter estimated to be 15% of the total cost in Europe [37]). Considering small GVHP plants built using local materials, a cost of 10,000 USD was estimated in a case study for Nepal (2015) [27]. The final summary of real costs incurred during the construction of our project is shown in Table 1 and Fig. 8. All of the values were calculated assuming an exchange rate of 1 USD = 3 PEN. It should be noted that design of the infrastructure, turbine, and electrical systems was done in-house. Hence, we did not need to pay for expert consultation for these technical tasks. Despite lower labor costs than other parts of the world, labor was our major cost during construction of the GVHP. A large fraction of this cost was for the excavation of the channels and tank (which was done manually as we could not access the site with machinery). Around 250 man-day were required for excavation (which included around 50 man-day for removing rocks in the channel), 180 man-day for cement works to form the inlet, outlet, and overflow channels, and the tank, 70 man-day to construct the dyke and gates, 24 man-day for turbine construction and installation, 12 man-day for gearbox installation, and 12 man-day for installation of the alternator and associated electrical components. Materials (including cement, steel, and wood) were the next largest cost, followed by consumables (including hardware, tools, and fuel for running a cement mixer and water pump). The transmission and electrical systems had a combined cost of around 20% of the total investment. The final costs of the construction are highly dependent on the site location and river conditions. For example, at our site, we needed a total length of around 100 m between the inlet and outlet to achieve the required head, which was determined by the slope of the river. For rivers with larger slopes, shorter channel lengths are required, which would reduce the construction and materials costs. We also encountered enormous rocks while excavating, which required a lot of time to remove, which inflated the labor costs. Dhakal et al. [28] also noted that labor costs are a determining factor in the construction of such plant and recommended that they be minimized as much as possible. We estimated use of around 60 m³ of concrete for the entire system, corresponding to around 15–20 m³/kW, which is much higher than a typical MW-scale hydroelectric plant (< 1 m³/kW).

In Peru, the cost of domestic electricity is ~0.1 USD/kWh [38]. Hence, assuming continuous generation of 3.1 kW throughout the year, we can generate over 27 MWh annually (2700 USD worth of electricity per year). Considering the total investment cost of 44,700 USD, the payback would be around 16 years. Considering that no optimization of the turbine was undertaken for this initial case study, we expect that the efficiency of the system can be increased to at least 30%, as achieved for similar systems [26]. If so, this would reduce the payback time to around eight years. This is similar to the period claimed by commercial manufacturers of the GVHP technology [37]. Our installation case was quite expensive compared to e.g., the average cost of around $3500/kW of micro-hydropower installations in Nepal [28] (mainly due to the large labor costs described above). We have not operated our system long enough to estimate maintenance costs, but a similar 10-kW-scale system in operation since 2006 has shown annual maintenance costs around 1000 € [37]. The plant is fully owned by the research group.

Table 1
Final breakdown of costs for our GVHP system.

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost (USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials (e.g., cement, wood, steel)</td>
<td>7400</td>
</tr>
<tr>
<td>River side infrastructure (gabions, dyke, and gates)</td>
<td>2500</td>
</tr>
<tr>
<td>Consumables (e.g., hardware, tools, fuel)</td>
<td>7300</td>
</tr>
<tr>
<td>Electrical system (e.g., generator, cables, dump load, controllers)</td>
<td>3800</td>
</tr>
<tr>
<td>Transmission (gearbox, bearings)</td>
<td>5000</td>
</tr>
<tr>
<td>Turbine (axles, blades, bearings)</td>
<td>1200</td>
</tr>
<tr>
<td>Labor</td>
<td>17,500</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>44,700</strong></td>
</tr>
</tbody>
</table>

Fig. 7. (a) System efficiency as a function of turbine speed for our system compared with a small-scale experimental system [34]. (b) Turbine efficiency of our system compared with that of a commercial GVHP system [17] and competing low-head technologies (an overshot water wheel with a diameter of 3.6 m [35], and an Archimedes screw turbine [36]).

Fig. 8. Pie chart showing the breakdown of the system costs.
which has responsibility for its maintenance.

Comparison with other low-head technologies

Here, we briefly compare the GVHP technology to existing low-head technologies in order to critically evaluate the technology. Considering the river conditions (head and flow rate) and output power (few kW to tens of kW), the major competing technologies are water wheels (e.g., Sagebien and Zuppinger designs) and reverse-running Archimedes screw turbines.

Water wheels are a very mature technology, and have been thoroughly investigated and consistently used over the past few hundred years. Undershot water wheels operate at very similar conditions to the GVHP, such as 1.2–2.3 m head and up to 3 m$^3$/s flow rate [35]. A noted disadvantage of Zuppinguer water wheels is the low frequency (3–4 Hz) noise produced when the water hits the blades, which is particularly irritating to humans and has caused problems when these plants are installed close to residential areas [39]. Such problems have not been noted for the GVHP technology. The low rotational speed of water wheels can also be a disadvantage for electricity production as high ratio gearboxes (e.g., 1:100) are required, which are expensive and can account for 25–30% or 40–45% of the total cost of undershot or over-shot systems, respectively [40]. For power generation, a constant speed and controlled inflow is preferable, which can be difficult to achieve with water wheels as active control is required to maintain the high efficiency of the turbine [35]. This is also expected to be a challenge for the GVHP system as both technologies show steep changes in efficiency with turbine speed and flow rate [28,40]. Electronic control of the frequency can be performed using an ELC, such as in our case study, but some mechanical governing of the water flow is desirable in order to minimize efficiency drops with changes in the water conditions.

A recent study experimentally compared the GVHP technology with an undershot water wheel and investigated the torque, energy of the turbine, and overall efficiency at flow rates of 0–0.016 m$^3$/s and a head of 0–0.5 m [34]. They concluded that the GVHP system was favorable, as an efficiency of 35% was achieved compared to that of < 14% for the water wheel. However, the study provided a limited analysis, as it is well known that the flow rate, turbine speed, and turbine geometry need to be carefully optimized to ensure maximum efficiency. Water wheels have been shown to achieve high efficiencies of 70–80% [35], which is at least double that currently demonstrated for most GVHP systems. Payback periods of 7.5 years and 12–14 years have been proposed for undershot and overshot water wheels, respectively, which is similar to the 8–16 years for our system, and significantly shorter than the 25–30 years for Kaplan systems [39].

Archimedes screw systems share many of the advantages of GVHP. Both can be installed alongside rivers, resulting in a short depletion distance (distance between where the water leaves the river to enter a hydro system and where the water is returned to the river); long depletion distances can compromise the ecology of the river bed [36]. It is expected that Archimedes screws require less civil works than the GVHP, and are debris tolerant. However, like some water wheels, they require variable-speed operation to ensure high efficiency, and operate at very low speed. In addition, we expect that the heavy metal Archimedes screw turbines would be difficult to transport and install in remote locations that are inaccessible to heavy machinery. An advantage of the GVHP for remote installations is that the largest structure (the concrete tank) can be constructed on site using manual labor (as we demonstrated), while the turbine can be transported in parts and assembled on site.

Water vortices often occur in industrial settings, particularly in water treatment plants, and are used extensively in hydraulic engineering. Hence, the GVHP could have niche applications in industry for generating energy from existing vortex formations, which would eliminate the need for constructing additional channel and tank infrastructure. Many of the proposed environmental advantages of the GVHP, such as water aeration, fish passage, and no need for large dams, also apply for many low-head hydro systems.

Conclusions

Here, we detailed the design, installation, and testing of a 10 kW-scale GVHP plant. This technology was shown to be highly suitable for operation with a head as low as 1 m with a minimum flow rate of 0.5 m$^3$/s. Such hydropower systems are very promising for application in developing countries, in particular in tropical regions where there are strong rivers that flow year-round. We demonstrated that the infrastructure required for this technology could be constructed with a high level of manual labor, with materials and technologies available for purchase or manufacture in a developing country. Other than the alternator and gearbox, all parts were manufactured either in-house or locally. All civil works were completed on-site using unskilled labor under the guidance of the designer/engineer (first author). We think that the relatively small investment cost and short payback time make it especially interesting for small rural communities where connection to the grid is prohibitively expensive or unavailable. Significant cost reductions could be achieved by selecting a site with higher river slope (available head). Compared to existing low-head hydropower technologies such as water wheels, the GVHP system is still immature and further research is required to optimize the tank and turbine geometry in order to increase the practical operating efficiency and make this technology more economically viable. Further theoretical studies are required to quantify the maximum achievable efficiency, which could be limited by the presence of the air core. Perhaps this technology is the most viable for sites where the advantages of the simplicity of the system outweigh the need for high efficiency. Testing of up-scaled systems to verify the results of experimental-scale systems is vital. Considering the challenging high-torque operating conditions, we identified that the transmission is a limitation of the GVHP system; hence, a contactless magnetic gearbox is being developed to overcome problems with the durability of mechanical gearboxes.

Acknowledgements

We are very grateful to the many people who helped in the construction of the hydropower plant, in particular Marcelo Ramos Martel, Pablo Cisneros Valdés, and Fredrik Stoltz. We appreciate fruitful discussions with Sean Mulligan (Institute of Technology, Sligo, Ireland). This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2019.06.004.

References
