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Review

Hydrokinetic turbines for moderate sized rivers

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Abstract

If hydrokinetic turbines are to make a significant contribution to small scale off-grid power supply, they will need to be affordable, reliable and easily deployed at many sites, not just a few with exceptional combinations of depth and high flow velocity. Few if any products currently on the market meet these criteria. This paper addresses the challenge of providing small scale electrical power and pumping from rivers, in particular for villages in high rainfall tropical areas where there is no mains power, not much wind or sunny weather in the wet season, and not enough elevation for conventional micro-hydro. Hydrokinetic power is proposed, and candidate turbines are evaluated, including multiple small axial flow turbines, various forms of horizontal axis Darrieus turbines, water wheels, and belt turbines. The importance of channel blockage in enhancing turbine power output is discussed.

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Introduction

Hydrokinetic turbine (HKT) technology has evolved from wind turbine technology and a few large (1 MW or more) axial flow tidal turbines resembling underwater wind turbines have been built and deployed at exceptional sites, notably the Pentland Firth off the north coast of Scotland, where the water is tens of metres deep and tidal flow velocities reach 3 m/s or more. There is also considerable interest in the potential of small (< 50 kW) hydrokinetic turbines to generate off-grid power from rivers, mainly for third world villages, but attempts to use scaled-down versions of large tidal turbines have met with little success for a range of reasons, as discussed in a previous publication (Kirke, 2019) and further explored below.

Potential problems with HKTs

Problems with small hydrokinetic turbines may include

1. High capital cost and low capacity factor
2. Low power density due to low flow velocity
3. Shallow water
4. Rocky stream bed reducing available space for turbine
5. The need to provide for boat passage in some rivers
6. Floating debris clogging turbines
7. Damage from floating logs
8. Unexpectedly high loading from eddies and flash floods
9. Difficulty deploying and retrieving turbines.

These issues are addressed below.

Capital cost and capacity factor

According to Dr. Barbara Sexon of Thropton Energy Services Thropton Energy Services, 2020 (Pers. Comm) “machines made in Europe and USA or Canada are likely to be too expensive for the people who really need them. The Garman turbine was initially developed in the Sudan primarily for water pumping along the Nile. ... The aim of the work was to produce a turbine which could be manufactured and maintained in the region, using materials, hand tools and machinery available in the local manufacturing sector. The company objective was to sell expertise rather than equipment...” The present author has been trying to transfer expertise to Sarawak and Peru, but advancing age and the Covid-19 pandemic are preventing further progress.

Capital cost compared with alternative power sources

It is difficult to find prices for HKTs to assess their cost-effectiveness relative to other power supply options. Table 1 lists those that the author has been able to find.

For comparison, diesel gensets up to about 6 kW are available for less than $2000 AUD ($1400 USD) and although running costs are significant and diesel supplies may be difficult to transport into remote sites, communities with very limited cash are likely to choose this option rather than an expensive HKT that will only deliver a few hundred Watts, even if this output is continuous and silent. Solar photovoltaics are available for about $1000 per peak kW or $5000 per average kW in sunny weather, but they require battery storage to deliver power on demand, unlike HKTs which will produce power whenever the river is flowing.

Capacity factor

As discussed in Kirke (2019), most manufacturers of HKTs quote rated power in about 3 m/s flow velocity, but such flows are rare in rivers, and because power increases with velocity cubed, this gives a very misleading impression of the energy that can be expected from a HKT in a typical river. For example a turbine rated at 5 kW in a 3 m/s flow will only deliver $5 × (2/3)^3 = 1.5$ kW in a 2 m/s flow and 0.18 kW in a 1 m/s flow.

Flow velocity and power density

The Garman turbine was among the first designed to pump water, and Thropton Energy (http://www.throptonenergy.co.uk/) developed a range of conventional axial flow designs resembling wind turbines, ranging from 1.8 to 4 m diameter. They also offered area and site surveys, market surveys, licenses and training for local manufacture. A

Table 1

| Company                    | Hardware                                                                 | Rated power, kw | Current m/s for rated power | Min depth, m | Dimens-sions, m Note 1 | Price USD | Avail-able? Note 3 |
|----------------------------|--------------------------------------------------------------------------|----------------|-----------------------------|--------------|------------------------|-----------|-------------------|
| New Energy Corp Canada*    | Vertical axis turbine, complete off-grid system                          | 5              | 3                           | 1.5 dia × 0.75H | Note 2       | 10 000    | y                 |
|                            |                                                                          | 10             | 1.87                        | 1.5 × 1.5    | y                      | 14 000    | y                 |
|                            |                                                                          | 25             | 27                          | 3.4 dia × 1.7H| y                      |           |                   |
| Smart Hydro Germany        | Free Stream Turbine, Generator, structure incl. debris protection, anchoring cables, and 50 m electrical cable Monofloat Turbine, Generator, shroud, debris protection, float, side anchoring set, anchor buoy set, 50 m electrical cable Grid-connected inverter, controller, dump load, and fuse box) 10 kWh, 48 V battery bank | 5              | 3.1                         | 1 m dia      | Note 2       | 16 342    | y                 |
| New Energetics USA.        | One-speed motor, 1-phase or 3-phase output. Plug-in ready                 | 1              | 1.2                         | 0.64 m dia   | 8 000       | n         |                   |
|                            | Two-speed motor, 1-phase or 3-phase output. Plug-in ready                 | 5              | 2                           | 13 500       | n         |                   |
|                            | Two-speed motor, 1-phase or 3-phase output. Plug-in ready                 | 10             | 2.5                         | 20 000       | n         |                   |
| Idenergie Canada           | Small horizontal axis Darrieus turbine Floating water wheel               | 0.5            | 3                           | 0.6          | ?          | 10 000    | ?                 |
| Greenergy Hydrocat         |                                                                          | 0.183          | 1                           | 16 600       | n         |                   |
| Waterrotor Canada          | **estimated target prices**                                             | 1              | 1.8                         | 75 000       | n         |                   |
|                            |                                                                          | 10             | 1.8                         | 50 000       | ?         |                   |

Notes: 1. Overall dimensions of mounting structures are generally much greater than those of just the rotating turbine. Some manufacturers offer alternative mounting arrangements and the reader is directed to the relevant web pages. 2. New Energy offer complete systems up to 250 kW, but only those requiring depths <2 m are listed above. A price of $50,000 negotiable for a 5 kW system was mentioned but not put in writing. 3. There is doubt as to whether some of the manufacturers tabulated above can actually supply.
flow velocity of at least 0.5 m/s was required, up to 1.5 m/s. These are realistic velocities for typical sites, but the required depth of at least 1.75 m for the 1.8 m diameter turbine would exclude it from many sites. Fig. 1 shows a Garman-Thropton turbine in a river.

A 0.5 m/s flow velocity contains very little kinetic energy. Kinetic energy flux or power density = \( \frac{1}{2} \rho AV^3 \) where \( \rho = \) water density = 1000 kg/m³, \( A = \) flow area intercepted by turbine and \( V = \) free stream velocity. So a 0.5 m/s flow has a power density = \( \frac{1}{2} \times 1000 \times (0.5)^3 = 62.5 \) W/m², and the 1.8 m diameter Garman turbine with a swept area of 2.55 m², if fully immersed, would intercept 159 W of kinetic power. So the turbine plus generator with a combined efficiency of say 30% would deliver 47.7 W. This may be enough to trickle charge a battery or pump a small amount of water at low head, but not much else. However this is the bottom end of the Thropton range, and it is claimed that up to 2 kW can be generated at higher velocities.

High flow velocity is crucial. Although velocities around 3 m/s have been measured in a few places such as the Colorado River in Utah (Magirl et al., 2009), these are exceptions and are unlikely to be found at sites near consumers where small-of-grid HKTs can be useful. As shown in Table 2, typical river velocities are generally <1 m/s, and although there are places with higher velocities, these higher velocities generally coincide with shallow depth, or they occur on the outside of bends where flow can be very non-uniform, making it difficult to locate turbines.

### Shallow water

Aside from very large rivers which rarely flow above about 1 m/s, as shown in Table 1, most rivers are only a few metres deep. Even in relatively large rivers such as the Ohio and Willamette, depths at most sites are <2 m, as shown in Fig. 2, after Andreadis et al., 2013.

Fig. 3 shows a boat negotiating a shallow, fast-flowing stretch in a river where the outboard motor must be raised due to lack of depth. This site might be suitable for a turbine that can operate in very shallow water with provision to allow boats to pass.

### Channel blockage, efficiency, hydrokinetic and ultra-low head turbines

Although it is not made clear in most references, a critical performance factor in any in-stream turbine is the degree of blockage in the waterway. In open flow, where there is plenty of space around the turbine for the flow to go around it, any wind or water turbine has an upper limit of "efficiency,” or coefficient of performance \( \eta \), the ratio of mechanical energy extracted to kinetic energy in the undisturbed flow area equal to the swept area of the turbine. This is the Betz limit of 59.3%.

But in relatively small waterways where a turbine takes up a significant portion of the flow area, there is less space for the flow to bypass the turbine, so the upstream water level rises slightly and there is a small drop in level across the turbine, i.e. potential energy is now involved and more power can be extracted (in fact there is always a small drop in level across any HKT, but accelerated flow around the turbine and mixing downstream make this drop almost imperceptible, leading to the widespread idea that HKTs are “zero head” turbines.)

Water flows fast where gradients are relatively steep, so high blockage turbines with slight drops in water level can be relatively closely spaced along fast flowing rivers.

The increased power from a "hydrokinetic" turbine with blockage was illustrated by measurements in a laboratory flume by McAdam et al. at Oxford University (McAdam et al., 2013). They found that a

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**Table 2**

| River/site                  | State | Mean velocity, m/s |
|-----------------------------|-------|--------------------|
| Kuskokwim/Crooked Creek     | AK    | 1.01               |
| Yukon/Pilot Station         | AK    | 0.88               |
| Connecticut/Thompsonville   | CT    | 0.86               |
| Apalachicola/Chattahoochee  | FLA   | 0.52               |
| Ohio/Metropolis             | IL    | 0.87               |
| Mississippi/Clinton         | IA    | 0.58               |
| Penobscot/West Enfield      | ME    | 0.72               |
| Missouri/Culbertson Rapids  | MT    | 0.74               |
| Roanoke/Corralee Rapids     | NC    | 0.62               |
| Red River North/Grand Forks | ND    | 0.58               |
| Missouri/Nebraska City      | NE    | 1.36               |
| Humbold/Imlay              | NV    | 0.37               |
| Arkansas/Tulsa              | OK    | 0.78               |
| Rogue/Apness                | OR    | 0.76               |
| Brazos/Richmond             | TX    | 0.57               |
| Sevier/Juab                 | UT    | 0.46               |

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**Fig. 2.** Depths of two large US rivers, after Andreadis et al. (2013).
Darrieus turbine that would have achieved $C_P$ no more than about 0.35 in open flow, produced an apparent $C_P$ just over 1 where blockage was about 60%. This is clearly impossible if only kinetic energy was involved, so there must have been some conversion of potential energy. Kinsey and Dumas (2017) found a similar effect, as shown in Fig. 4, showing that the effect is more significant for cross flow than for axial flow turbines.

This effect is very important in small and moderate sized rivers where the available energy is limited, and it may be practicable for a turbine to occupy most of the flow area — provided

1. There is provision for boats to pass where required
2. The banks are stable, or can be stabilised, and the turbine is not likely to be washed away by flash floods.

To confine the flow for any type of turbine, it may be necessary to build a low weir on each side to restrict low flows, while allowing high flows to pass over like a spillway without scouring the banks or the riverbed.

Fig. 5 shows a deep, slow part of a river in Sarawak with very low power density in the foreground, flowing into a shallow and fast stretch with much higher power density where a wide, shallow turbine might be placed with high blockage in low flows, with a small weir on the right to allow high flows to pass without scouring the bank. The turbine would have to be designed so one end could swing to allow boats to pass.

A similar arrangement might be possible at high energy sites such as those shown in Fig. 6, which are rocky and shallow, but with a weir and a high blockage turbine, the upstream water level could be raised enough to overcome this difficulty.

**Turbine choice**

Single axial flow (propeller type) turbines like that shown in Fig. 7 are not suitable for significant power delivery from rivers unless there is deep, fast-flowing water, as they require depth greater than the diameter to be fully immersed, and their swept area $A$ is equal to $\pi r^2$, where $r =$ radius, so for example a turbine with a diameter of 1 m (radius $r =$ 0.5 m) has a swept area of 0.8 m² and requires a depth well over 1 m for optimum performance, although it will still work partially immersed.

Fig. 8 shows a 1 m diameter Smart Hydro Monofloat turbine being launched. It is manufactured by Smart Hydro Power GmbH (Ltd.), a private company financed by the German Ministry of Economics and

![Fig. 3. A shallow, fast-flowing stretch in a river near Telinting in Sarawak where the outboard motor must be raised due to lack of depth (photo by author).](image)

![Fig. 4. The effect of channel blockage $\epsilon$ on drag coefficient $C_D$ and performance coefficient $C_P$ for axial flow HKTs (left) and cross flow HKTs (right), after Kinsey and Dumas (2017).](image)
several German corporations like Siemens and Bosch, followed by the German cleantech fund eCapital and the German development bank KfW (Smart Hydro Power: about us. Undated). Smart Hydro Power Renewable Energy Solutions, 2020

It is claimed (https://www.smart-hydro.de/decentralized-rural-electrification-projects-worldwide/) Smart Hydro Power Decentralized Rural Electrification, 2020 that >40 of these units have been sold, making it the most successful river turbine so far produced. However it weighs 380 kg, requires 2 m depth and 2.8 m/s current velocity to achieve its 5 kW rated power output, and as shown in Table 1, costs USD $16,400. Clearly a lighter turbine able to operate in shallower water would be easier to deploy as well as being useful at a wider range of sites.

The cables on the upstream (left hand) side of this turbine provide some protection from floating debris, which was identified by M. Anyi (2013) and M. Anyi and Kirke (2015) as a major problem in many rivers worldwide, leading to the development of an axial flow turbine with blades that are free to swing back and shed debris when hit by a floating log or clogged with weed etc., shown schematically in Fig. 9.

To maximize swept area in shallow water and wherever possible gain the advantage of blockage, a wide, shallow turbine is needed, or alternatively multiple small turbines arrayed across the flow. Possible options include

(i) Multiple small turbines arrayed across the flow
(ii) Darrieus turbines with straight, fixed pitch blades
(iii) Darrieus turbines with variable pitch blades
(iv) Darrieus turbines with helical blades
(v) Savonius rotors
(vi) Waterwheels
(vii) Belt turbines.

Fig. 5. The river at Long Anyat, Sarawak: foreground deep and slow, downstream shallow and fast (photo and annotation by author).

Fig. 6. Left: students in Huanaco, Peru, attempting to launch their experimental HKT. Right: The Rio Chili in Arequipa, Peru (photos by the author).

Fig. 7. A Schottel axial flow (horizontal axis) turbine (http://www.blackrocktidalpower.com/fileadmin/data_BRTP/pdf/STG-datasheet.pdf) Schottel Hydro, 2020 and a New Energy Corp cross flow (usually vertical axis) hydrokinetic turbine (https://www.newenergycorp.ca/envirogen-005-series.html). New Energy Corporation, Calgary, Alberta T2L 2K7 Canada, 2020
These forms of turbine are reviewed below, with actual examples where these have been found.

**Multiple small turbines arrayed across the flow**

Fig. 10 shows a low cost, 0.6 m diameter axial flow turbine developed at the University of Malaysia, Sarawak Campus (UniMaS), made from fan blades and aquaculture floats, easily transported and deployed due to its small size. It developed about 110 W in 1.2 m/s flow. This would be useful if only 110 W is required, but most applications need more power.

Multiple small turbines like this could be deployed side by side, perhaps with inclined shafts and direct drive like the Garman turbine shown in Fig. 1 to eliminate the right-angle drive. A possible arrangement is shown schematically in Fig. 11, and it would also be possible to use multiple small vertical axis Darrieus turbines in a similar arrangement.

**Darrieus turbines with straight, fixed pitch blades**

Vertical axis Darrieus turbines (Fig. 7) can in theory be made with large diameter D and short blade height H, but then they rotate at low RPM, requiring a large step-up gear ratio, and Darrieus radial arm parasitic drag losses increase, reducing efficiency. Although normally mounted with axis vertical and commonly referred to as “vertical axis turbines,” Darrieus turbines can be mounted with axis horizontal. Two examples are shown in Fig. 12, the Idenergie Inc., Montreal, Canada, Idenergie Inc., Montreal, Canada, 2020 (http://idenergie.ca/en/news/) and the New Energetics Inc. New Energetics Inc., Cleveland, USA, 2020 (http://www.new-energetics.com/main/turbinepopup.aspx?format=3) turbines.

The Idenergie turbine is basically a pair of small Darrieus turbines driving a generator directly. It costs about USD 10,000, can operate in 0.6 m depth and 1 to 3 m/s flow, and is claimed to be able to generate “up to 12 kWh per day” – so rated power is presumably 500 W in 3 m/s flow. Fig. 13 shows that deployment can be difficult despite its small size and depth requirement. According to a 2016 post on their website, they were “currently actively seeking partners to assist … with … commercialization efforts.” The only installations mentioned were financed by the Build in Canada Innovation Program and at the time of writing (May 2020) there has been no news on their website since 2017, so it has apparently not been a commercial success.
The New Energetics “orthogonal” turbine is a variant on the Darrieus, with a long shaft and several short blades at different azimuth angles, in some ways resembling a discontinuous helical turbine in that torque ripple is reduced in comparison to the standard Darrieus turbines with only three blades. The model shown has six blades at 60° intervals, but modelling by the author has shown that eight blades are needed to produce smooth torque, as shown in Fig. 14.

Similar effects occur with radial force, although it does not vary as steeply with azimuth angle as tangential force. One big advantage of this arrangement of multiple short blades is that there is only one blade in each cross section, so the effective solidity \( \sigma = \frac{n c}{r} \) where \( n \) = number of blades, \( c \) = chord length and \( r \) = radius is kept relatively low on a small diameter turbine, which enables it to operate at high enough tip speed ratios (above about 3) to avoid stall, while chord

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**Fig. 11.** A possible arrangement of multiple small axial flow turbines on inclined shafts driving a single generator (image by the Author).

**Fig. 12.** Left: Idénergie Inc. and Right: New Energetics Inc, Cleveland, USA, 2020. turbines.

**Fig. 13.** Deployment can be difficult in fast flows, even for small turbines (image from http://idenergie.ca/en/news/).
length can be large enough to achieve acceptably high blade chord Reynolds numbers. Kirke (2016) has demonstrated that the performance of Darrieus turbines decreases sharply as Reynolds numbers decrease below about 200,000. He has built such a turbine with diameter 1 m and chord length 0.16 m, giving an effective solidity of 0.32, which is ideal, and a Reynolds number ranging from 640,000 to 320,000 at a tip-speed ratio of 3 in a 1 m/s flow, as the blade moves upstream then downstream.

Another advantage of multiple short blades is that the bending moment on both the long shaft and the blades is less than it would be with continuous blades. Short blades with low aspect ratio generally perform poorly due to relatively large tip losses, but in this design the radial arms should limit tip losses. The large number of radial arms will produce significant parasitic drag loss, but if they are of hydrofoil profile, they may actually behave like Wells turbines and generate some additional power when the flow is not quite normal to the shaft.

Chord-radius ratio and flow curvature

The chord-radius C/R ratio on the New Energetics turbine shown in Fig. 12 appears to be about 0.5, which is very high. Migliore et al. (1980) found that a Darrieus turbine with C/R = 0.26 achieved a peak C_P of only 0.15 compared to 0.39 for C/R = 0.114, so it would be expected that the New Energetics “orthogonal” turbine shown in Fig. 12 would perform very poorly, but it could easily be redesigned with smaller chord length. Migliore et al. (1980) attributed the poor performance at high C/R to virtual camber, i.e. a symmetrical foil in curvilinear motion behaves like a cambered foil in linear motion, but they did not take the next step and test the performance of cambered foils or a small degree of preset pitch, which has been found by some researchers to improve performance. For example Fiedler and Tullis (2009) “measured performance decreases of up to 47% for toe-in, and increases of up to 29% for toe-out blade pitch angles, relative to the zero preset pitch case.” Naoi et al. (2006) have reported on the use of blades with camber matching the curvilinear blade path, and this may solve the problem, but they did not report on the efficiency, and attempts to contact the authors have been unsuccessful.

The New Energetics website lists 1, 5 and 10 kW models designed to operate in 1, 2 and 2.5 m/s flows, with prices ranging from USD 8500 to 20,000, but enquiries by the author have failed to clarify whether the company can actually supply turbines to order.

Darrieus turbines with variable pitch blades

Most Darrieus turbines have fixed pitch blades and they suffer from lack of starting torque, shaking and torque ripple, but variable pitch ensures adequate starting torque, reduces shaking and torque ripple (Lazauskas & Kirke, 2012) and can achieve good efficiency (around 40%) at high solidities up to 0.7, where fixed pitch Darrieus turbines have low efficiency (Winchester & Quayle, 2011). The author has developed and patented a simple variable pitch system (Kirke, 2012), shown in Fig. 15 (left). It was demonstrated in 2011–12 mounted with axis vertical and was later donated to the Universidad Nacional de San Agustín (UNSA), Peru, where it was demonstrated operating part-submerged in a canal shown in Fig. 15 (right).

It will be apparent from Fig. 16 (modified from Lazauskas and Kirke, 2012) that at tip-speed ratios around 2, most of the power is extracted when blades are moving upstream (0 < θ < 90° and 270° < θ < 360°), so part-submerged operation can be almost as effective as fully submerged operation, an important finding for shallow sites. But at tip-speed ratios λ of 3 or more, nearly all of the power is extracted on the
upstream pass (0 < θ < 180°), as shown in Fig. 16, so a large diameter shaft needed for the high bending moments on a long turbine spanning most of the width of a river would probably have little effect on the turbine's performance.

A three-blade version of the New Energetics turbine with arc camber blades, able to operate in either fixed or variable pitch modes, was built and tested in Australia in 2019–20. As expected, it failed to self-start in fixed pitch mode and although it self-started in variable pitch mode, it shook so violently that it was not possible to measure its performance. A four-blade version was built in Sarawak in 2019 but according to Dr. Anyi “was almost impossible to test” (probably due to its weight and depth requirement, site access difficulties and limited manpower available). It was clear that multiple blades would be necessary for smooth operation, as indicated in Fig. 14.

**Darrieus turbines with helical blades**

Helical (“Gorlov”) turbines are a variant on the Darrieus and have the advantage that torque ripple is nearly eliminated, but variable pitch is not possible and tests conducted by the author with Coastal Hydropower Corporation (Kirke, 2011) found that, contrary to some claims, starting torque was still a problem. Maximum Cp for the high solidity turbines tested was no >25%. The ORPC (Ocean Renewable Power Company) turbine array shown in Fig. 17, from [https://www.orpc.co/our-solutions/scalable-grid-integrated-systems/tidgen-power-system ORPC Inc, 2020a], has four turbines driving a single generator and is claimed ([https://www.offshore-energy.biz/us-government-funds-orpc-rivgen-system/]ORPC Inc, 2020b) to generate 25 kW. This arrangement avoids large bending moments on the shaft, and although the support structure shown would require several metres depth, a scaled down version would be possible. Although millions of dollars have been spent on the development of this turbine according to several websites, e.g. [https://www.offshore-energy.biz/orpc-to-use-usd-3-8m-funding-to-develop-hydropower-tech/], there is no mention of multiple units being built except for various prototype arrangements, a tidal version and a river version, and it is not clear what the unit cost of a production model would be.

**Kepler Energy**

The Kepler Energy “THAWT” (Transverse Horizontal Axis Water Turbine) concept (Fig. 18) Kepler Energy, 2020 uses a different approach to large bending moments. Resembling a modified helical
turbine, it is in fact a space frame structure, designed by structural engineers at Oxford University.

According to the Kepler Energy website [https://keplerenergy.co.uk/technology.html], “Theoretical analysis and modelling, confirmed by testing, has shown outputs several times higher than those achievable by propeller type turbines placed in the same site. This advantage arises from (1) the greater rectangular swept area of a THAWT rotor compared with the depth limited circular swept areas of multiple propeller type rotors and (2) the fact that greater powers can be extracted from tidal flows by optimising the blockage ratio (swept area of turbine divided by flow area).” Unfortunately, Kepler Energy has so far failed to attract the funding to progress beyond the model stage.

Savonius rotors

Savonius rotors (Fig. 19) are simple, and although most investigations indicate low efficiency, Rahai (2005) suggests that it may be possible to make them more efficient. In particular, Rahai’s optimised rotor (Fig. 20) looks very promising, but it would need some sort of truss structure to withstand the bending moments on a long turbine and Rahai has not responded to attempts to contact him to ask if there has been any commercial development.

The Waterotor shown in Fig. 21, from https://waterotor.com/our-solution/Waterotor Energy Technologies Inc, 2020a, bears a slight resemblance to a three blade Savonius rotor with a deflector plate. The Waterotor website makes extravagant claims but gives no information on performance. “Estimated target prices” are given at https://waterotor.com/products/#specs. Waterotor Energy Technologies Inc, 2020b

Waterwheels

Waterwheels can be driven by either flowing or falling water, or a combination of both. The “stream wheel” shown in Fig. 22, from https://en.wikipedia.org/wiki/Water_wheel#Undershot_wheel, is effectively an HKT. They are simple but bulky for their power output, and they rotate very slowly, with optimum efficiency achieved when the paddles are moving at ½ - 1/3 of the water velocity, making them unsuitable for driving generators, compared with axial flow turbines with tip-speed ratios of 4 or more, 2.5–3 for Darrieus and 1 for Savonius rotors. Although they are normally narrow with a large diameter, there seems no reason why water wheels could not be made wide to intercept more flow in a shallow river. M. Anyi (2013) found three images of large, fairly wide floating waterwheels, one of which is shown in Fig. 23. These are referenced in Table 3. They are all different in appearance, located in three different countries, published in 2003–5, with no evidence of more recent developments along similar lines, suggesting that they were one-off prototypes and further development was not deemed justified.

Waterwheel diameter could be reduced to increase RPM, which would reduce the necessary gearing. The paddles could be mounted on a long, buoyant, hollow cylinder which could resist the high bending moments and enable it to float. To illustrate this concept, the author built a model 1.5 m wide from a single 6 m length of 150 mm diameter PVC pipe costing about AUD 80, but was not able to test it due to lack of support personnel.

The Greenenergy Hydrocat [Greenenergy Hydrocat waterwheel, 2020]

Several YouTube videos (e.g. https://www.youtube.com/watch?v=H3_jPbQ2iuc) were found describing a waterwheel mounted between...
a pair of hulls, shown in Fig. 24. A pdf has also been found, giving dimensions, prices and output, ranging from a 1.25 m diameter rotor 1.5 m wide, claimed to generate 183 W in 1 m/s current and costing €14,700 to a 40 kW model costing €66,400. But the pdf has disappeared and there is no contact point for potential purchasers.

Waterwheels for pumping

Although waterwheels are not generally suitable for driving electrical generators, they can drive low speed pumps such as the coil pump shown in Fig. 25, from FAO Hydropower, 4.9.4, Water Wheels and Norias, 2020.
Waterwheels which block 100% of the flow

Hydrostatic pressure wheels (HPWs) or hydrostatic pressure machines (HPMs), whose power depends on static head and volumetric flow through the turbine, can be very efficient (> 80%) based on head and discharge, as shown in Fig. 26, after Senior et al. (2010). These would be suitable for lined channels with steep gradient such as the one shown in Fig. 15.

The HPW is much more compact than the traditional water wheel and may have a large cylindrical hub which can be buoyant and could be designed to withstand the large bending moments on a long turbine supported at each end. It would be possible to design a long waterwheel with high but not necessarily 100% blockage in low flows, which would achieve much higher efficiency than a stream wheel in open flow, and could float up on high flows to avoid damage.

Fig. 23. A floating waterwheel generator in Congo (Hydraulienes for Villagers, 2004).

Table 3
Large floating waterwheels (M. Anyi, 2013).

| Floating Mill on River Mura, Slovenia, 2005, Wikimedia Commons. |
| Floating waterwheel driving a coil pump (FAO Hydropower, 4.9.4, Water Wheels and Norias, 2020). |

Fig. 24. The Greenenergy Hydrocat waterwheel.

Fig. 25. A waterwheel driving a coil pump (FAO Hydropower, 4.9.4, Water Wheels and Norias, 2020).
Belt turbines

A belt turbine (Fig. 27) has a series of foils or sails mounted on a pair of endless belts, ropes or cables so they travel across the current and drive pulleys and a generator. Because they travel in an essentially straight path between pulleys, their angle of attack is essentially constant, unlike that in a Darrieus turbine, and so can be optimised, and because the pulleys driving the generator can be made small, RPM can be high compared with other turbines. However the transverse load on the blades causes very high tensile forces in the belts and radial loads on the pulley bearings. The company Tidal Sails AS has demonstrated several prototypes and patented one version, but is focused on large scale tidal flows, and the concept could be simplified and scaled down for rivers.

Loads

For the purposes of the present study, the initial aim is to supply enough low voltage DC power to keep a battery bank charged and power lights, fans and a small refrigerator for small villages typically situated on the banks of rivers like those shown in Figs. 3, 5 and 6. Later, larger power units might power a small community workshop beside larger rivers. A need has also been expressed (M. Anyi, pers. comm) for a pump to lift water from the river, and filtration to remove silt.

Generators and transmissions

All turbines listed in Table 1 come complete with generator, so a discussion of generators per se is not necessary in the present review. These are typically direct drive “PMG” or permanent magnet generators, which produce variable frequency 3 phase AC, which must be conditioned using power electronics, which according to https://www.newenergycorp.ca/technology.html serve two main functions:

1. To take the uncontrolled output from the generator and convert it to a form that is usable for the intended load.
2. To control the speed of the turbine so as to maximize power output and manage any transient or off spec conditions.

Specifically, the permanent magnet generator converts the torque generated by the rotor into electrical energy. The output from the generator is a variable voltage AC signal which is rectified to DC and fed into an inverter. The inverter takes the DC signal as...
input and provides an AC output suitable for use by the end user electrical load."

**Pumps**

As well as electrical power, villages require water supply. According to Anyi (pers. Comm), villagers in Sarawak are accustomed to trical load.

Quoted prices as shown in Table 1 are likely to be beyond the reach of sites, i.e. affordability, reliability and ease of deployment at many sites. Several technologies are potentially suitable as power sources in shallow, moderate sized rivers, and these have been reviewed. Several are advertised on various websites and numerous prototypes have been built, but there are few if any products currently on the market that meet the criteria for successful deployment at many third world sites, i.e. affordability, reliability and ease of deployment at many sites. Quoted prices as shown in Table 1 are likely to be beyond the reach of subsistence village communities.

Of the turbine types assessed in this article, a modified version of the New Energetics orthogonal turbine appears to offer the best combination of properties: it is simple, potentially low cost, able to be built in developing countries with limited workshop facilities, and able create blockage in wide, shallow rivers.

**Declaration of competing interest**

There is no conflict of interest.

**References**

Andreadis, K. A., Schumann, G. J. -P., & Pavelsky, T. (2013). A simple global river bankfull width and depth database. Water Resources Research, 49, 7164–7168. https://doi.org/10.1002/wrcr.20440.

Anyi, M. (2013). Water Current Energy for Remote Community: Design and Testing of a Clog-free Horizontal Axis Hydrokinetic Turbine. PhD thesis, University of South Australia.

Anyi, M., & Kirke, B. K. (2015). Tests on a non-clogging hydrokinetic turbine. Energy for Sustainable Development, 25(2015), 50–55.

Hydropower, F. A. O. (2020). 4.9.4, Water Wheels and Norias (undated). 49. (pp. 7164–7168), 7164–7168 Accessed 7 August 2020 http://www.fao.org/3/ah810e/ 

Fiedler, A. J., & Tullis, S. (2009). Blade offset and pitch effects on a high solidity vertical axis wind turbine. Wind Engineering, 33(3), 237–246.

Greenenergy Hydrocat waterwheel. https://www.youtube.com/watch?v=H3_jPBQZ2uc (Accessed 7 August 2020).

Idénergie Inc., Montreal, Canada (2020). http://idednergie.ca/en/news/ (Accessed 7 August 2020).

Kepler Energy (2020). https://keplerenergy.co.uk/technology.html (Accessed 7 August 2020).

Kinsey, T., & Dumas, G. (2017). Impact of channel blockage on the performance of axial and cross-flow hydrokinetic turbines. Renewable Energy, 103, 239–254.

Kirke, B. K. (2011). Tests on ducted and bare helical and straight blade Darrieus hydrokinetic turbines. Renewable Energy, 36(2011), 3013–3022.

Kirke, B.K. (2012). Improved Cross Flow Wind or Hydrokinetic Turbines. Australian Patent Number 2012101179.

Kirke, B. K. (2016). Tests on two small variable pitch cross-flow hydrokinetic turbines. Energy for Sustainable Development, 31(April 2016), 185–193.

Kirke, B. K. (2019). Hydrokinetic and ultra-low head turbines in rivers: a reality check. Energy for Sustainable Development, Volume, 52(2019), 1–10.

Lazauskas, L., & Kirke, B. K. (2012). Modeling passive variable pitch cross flow hydrokinetic turbines to maximize performance and smooth operation. Renewable Energy, 45(Sept 2012), 41–50.

Magir, C. S., Gartner, J. W., Smart, G. M., & Webb, R. H. (2009). Water velocity and the nature of critical flow in large rapids on the Colorado River, Utah. Water Resources Research, 45, Article W05427. https://doi.org/10.1029/2009WR007731.

McAdam, R. A., Houlsby, G. T., & Oldfield, M. L. G. (2013). Experimental measurements of the hydrodynamic performance and structural loading of the Transverse Horizontal Axis Water Turbine: part 1. Renewable Energy, 59, 105–114.

Migliore, P. G., Wolfe, W. P., & Fanucci, J. B. (1980). Flow curvilinear effects on Darrieus turbine blade aerodynamics. J. Energy, 4, 49–55.

Naoi, K, Shiono, M, Katsuyuki, K, Suzuki, S (2006). A wind power generation system using the vertical axis wind turbine with arc camber blades. 16th Int Offshore and Polar Engineering Conference, 28 May – 2 June, San Francisco, ISPOE I-06-178.

New Energetics Inc., Cleveland, USA (2020), http://www.new-energetics.com/main/turbinepopup.aspx?format=3 (Accessed 7 August 2020).

New Energy Corporation, Calgary, Alberta T2L 2K7 Canada (2020), https://www.newenergycorp.ca/energygen-005-series.html (Accessed 7 August 2020).

ORPC Inc (2020a),https://www.orpc.co/our-solutions/ scalable-grid-integrated-systems/tidgen-power-system/(Accessed 7 August 2020).

ORPC Inc (2020b),https://www.offshore-energy.biz/us-government-funds-orpc-rivgen-system/(Accessed 7 August 2020).

Rahai, H. R. (2005). Development of Optimum Design Configuration and Performance for Vertical Axis Wind Turbine. California Energy Commission Energy Innovations Small Grant Program.

Schottel Hydro (2020), Schottel Industries GmbH, http://www.blackrocktidalpower.com/fileadmin/data_BRTP/pdf/STG-datasheet.pdf (Accessed 7 August 2020).

Schulze, K., Hunger, M., & Döll, P. (2005). Simulating river flow velocity on global scale. Advances in Geosciences, European Geosciences Union, 5, 133–136.

Senior, J., Saenger, N. and Muller, G. (2010). “New hydropower converters for very low-head differences.” Journal of Hydraulic Research Vol. 48, No. 6, pp. 703–714.doi:10.1080/00221686.2010.529301 # 2010 International Association for Hydro-Environment and Research.

Smart Hydro Power Decentralized Rural Electrification. https://www.smart-hydro.de/decentralized-rural-electrification-projects-worldwide/(2020), (Accessed 7 August 2020).

Smart Hydro Power Renewable Energy Solutions. https://www.smart-hydro.de/renewable-energy-solutions-developers/(2020), (Accessed 7 August 2020).

Thropton Energy Services (2020), http://www.throptonenergy.co.uk/(Accessed 7 August 2020).

Tidal Sails AS (2020), https://tidalsails.com/about/(Accessed 7 August 2020).

Undershot Waterwheel, https://en.wikipedia.org/wiki/Water_wheel#Undershot_wheel (2020), (Accessed 7 August 2020).

Waterotor Energy Technologies Inc (2020a), https://waterotor.com/our-solution/ (Accessed 7 August 2020).

Waterotor Energy Technologies Inc (2020b), https://waterotor.com/products/#specsheets (Accessed 7 August 2020).

Winchester, J., Quayle, S. (2011). Torque ripple and power in a variable pitch vertical axis tidal turbine. 9th EWTEC, Southampton.