Energy for Sustainable Development 78 (2024) 101370

Contents lists available at ScienceDirect

Energy for Sustainable Development

journal homepage: www.journals.elsevier.com/energy-for-sustainable-development

Towards more cost-effective river hydrokinetic turbines

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ARTICLE INFO

Keywords:
Hydrokinetic turbine
Shallow rivers
Cross flow
Horizontal axis
Flexible blade

ABSTRACT

There are thousands of rivers across the world where hydrokinetic turbines (HKTs) could be generating constant small but useful amounts of power for remote off-grid communities, but there are very few hydrokinetic turbines actually operating, and these are limited to expensive units in very large rivers. For a cost-effective hydrokinetic turbine (HKT), the power output per unit cost must be maximised. Besides the cost of materials and fabrication of the turbine itself, cost includes a mounting structure, transmission and battery or mains connection, transport to site, deployment and operation and maintenance. This paper discusses the factors that determine power output per unit cost - C_P, A, V, and proposes a radically new low-cost design which is expected to make small turbines affordable to off-grid communities located on moderate sized rivers and provide a basis for developing more cost-effective large turbines for grid connection: a horizontal axis single helix HKT with a flexible blade. This concept offers several advantages over conventional HKTs: (i) it can sweep a much greater flow area in shallow water, (ii) there is no need for a large, expensive pontoon or barge, (iii) a single helical blade maximises Reynolds number while maintaining desirable low solidity and eliminating the torque ripple inherent in straight blade Darrieus turbines, (iv) its cost per unit output is low, making it far more cost-effective than conventional designs, and (v) it is light and easily transported and deployed.

Introduction: the need

There are thousands of rivers across the world which could be generating small but useful amounts of power. Taking Sarawak as an example, in 2017 there were 400 remote villages and 12,480 households in Sarawak "not connectible" to the grid (Tan et al., 2021). These villages are typically situated beside rivers as shown in Fig. 1, for water supply, fish and transport. At most of these sites the topography makes conventional high head micro-hydro impracticable, and overcast weather in the wet season makes solar uneconomic.

According to Dr. Martin Anyi of Sarawak Energy Berhad (pers. Comm. 2022), some Sarawak villages now have solar power with 3 days' storage, but even this may not suffice in overcast weather in the wet season. Also Kalimantan, with similar topography and several times the population of Sarawak, is less developed, suggesting a potential market of many hundreds of villages or thousands of households across Borneo alone, with many thousands more across the world, in particular in the wet tropics. According to Aiau et al. (n.d.), "*PNG has an ambitious programme to provide electricity to 70% of its scattered population by the year 2030.*" At present only 2 % of the population in this high rainfall country has access to electricity. According to Igbinosun et al. (2021), "Globally, about 7.2 million people still do not have access to adequate electricity, and even those that do still depend largely on energy from fossil fuel. The over dependence on fossil fuel is adversely affecting our world..." According to Behrouzi et al. (2016) "one-third of the world's population does not have access to electricity but does have access to flowing water." It is clear that there is an unmet need for affordable, reliable, easily deployed HKTs to supply small scale power to these villages.

Numerous reviews

In recent years there have been many reviews of HKTs, including Khan et al. (2009), Lago et al. (2010), Ortega-Achury et al. (2010), Behrouzi et al. (2016), Kumar and Saini (2014), Yuce and Muratoglu (2015), and Sood and Singal (2019). These cite numerous references and generally outline the definition of HKT and the principles on which they operate. Some, e.g. Khan, define axial flow, cross flow, vertical axis, with illustrative diagrams, but none mention a horizontal axis cross flow Darrieus turbine, which is the focus of the present article.

Costs and availability in 2019

This author searched for and reported on the few companies that provided actual cost data on small HKTs on their websites in 2019

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https://doi.org/10.1016/j.esd.2023.101370
Received 15 August 2023; Received in revised form 18 December 2023; Accepted 25 December 2023

Fig. 1. Long Busang village, Sarawak.

Table 1
HKT prices current March 2019.

Company	Hardware	Price (USD)	Available?
New Energy Corp Canada	Vertical axis turbine, complete off-grid system, 5 kW in 3 m/s current	50,000 negotiable	y
Smart Hydro Germany 1 m dia, 5 kW in 3.1 m/s current.	Free Stream Turbine, Generator, structure incl. Debris protection, anchoring cables, and 50 m electrical cable	14,000	y
	Monofloat Turbine, Generator, shroud, debris protection, float, side anchoring set, anchor buoy set, 50 m electrical cable	16,342	y
	Off-grid electrical cabinet, inverter & dump load	9700	y
	Grid-connected inverter, controller, dump load, and fuse box)	3650	y
	10 kWh, 48 V battery bank	5550	y
New Energetics USA.	1 kW for flows up to 1.2 m/s. One-speed motor, 1-phase or 3-phase output. Plug-in ready	8500	n
	5 kW for flows up to 2 m/s. Two-speed motor, 1-phase or 3-phase output. Plug-in ready	13,500	n
	10 kW for flows up to 2.5 m/s. Two-speed motor, 1-phase or 3-phase output.	20,000	n
Idenergie	500 W in 3 m/s flow	10,000	?
Greenenergy	183 W in 1 m/s	16,600	n
Hydrocat	40 kW in 3 m/s	75,000	n
Waterotor	?	?	?
ORPC	20 kW?	?	?

(Kirke, 2020). The findings are reproduced in Table 1 below.

However very few companies survive long enough to offer real products. For example, Smart Hydro, considered one of the more successful companies in 2020, is no longer in production. It is therefore difficult to review "current technology," because "current" at the time of writing will no longer be current in a few years' time and reviews over 10 years old are of very little value regarding cost. The best that can be done is to review a few representative examples which provide data including price, required depth and design flow velocity for rated output. But the literature provides very little useful data on cost-effective HKTs.

Cost estimates in published literature

Kusakana (2014) gives cost estimates based on quotations from local South African distributors of generation equipment: HKT (1 kW) $7500, PV (1 kW) $3590, Diesel generator (7 kW) $1240, Converter(?) (6 kW) $3730, Battery (6 V, 360 Ah) $215, Wind turbine (7.5 kW) $26,900. But he assumes the hydrokinetic turbine efficiency to be 65 %, which is impossible in unrestricted open flow.

Miller et al. (2011) published an estimated cost of $12,743.90 for a bank of 16 water wheel river current turbines with 10 m^2 swept area in a 0.3 m/s river velocity, assuming 500 W, or 100 W per turbine, including $360 material cost, $4750 installation costs including site preparation, and $1276 labor costs per site. It is unclear whether the 10 m^2 swept area refers to one turbine or the whole bank, but according to Wiki, efficiency of stream (also known as free surface) water wheels is 50 to 60 %. So assuming efficiency $= C_P = 0.6$, power from a 10 m^2 water wheel in 0.3 m/s flow is given by

$P = C_P \tfrac{1}{2} \rho A V^3 = 0.6 \times 0.5 \times 1000 \times 10 \times 0.3^3 = 81$ W, so it appears that each turbine would need to be at least 10 m^2 and a big enough bank to provide useful power would be very large and cumbersome.

Emea et al. (2019) state that "for a hydrokinetic turbine the level of power output is directly proportional to the flow velocity. Therefore, the cost of its installation is reduced drastically from about $7,900 per installed kW to about $2,500 per kW" The logic of this statement is unclear.

According to Tham and Lewis (2020), "A Mako turbine costs between $20,000 and $70,000, depending on the power output and the location." This statement is too vague to be useful.

According to REAP (undated), the first commercial "RivGen" HKT was commissioned in July 2019 and is generating 35 kW for the village of Igiugig in Alaska. "Igiugig was awarded a grant for a second turbine which, combined with the first RivGen® device, smart grid technology and an energy storage system being installed in 2020, will bring Igiugig into a clean energy future." According to US Department of Energy (DOE, 2020), ORPC (ORPC (Ocean Renewable Power Company), n.d.) received $3.7 m funding for their second RivGen device, shown in Fig. 5. This suggests that the Rivgen needs huge subsidies to be viable.

Overall, these references give little indication of realistic prices for small HKTs.

The need for more cost-effective HKTs

Besides the need and the potential market for small HKTs, there is a need to develop more cost-effective designs, not only for rivers but also HKTs for tidal sites with lower flow velocities than those currently attracting most attention. Unlike river sites supplying small villages adjacent to rivers, where small HKTs are required, interest in tidal sites is generally focused on large turbines suitable for mains connection, but similar design principles are involved. The final report of the Australian Tidal Energy (AUSTEn) three-year project "*to map Australia's tidal energy resource in detail and assess its economic feasibility and ability to contribute to the country's renewable energy needs,*" released in November 2020, made 15 recommendations. Recommendation 1 was for *"Technical improvements to tidal energy converter (TEC) design to increase capacity factors that are then competitive in relation to the Australian available tidal resource."* (Penesis et al., 2020*)*.

Put simply, this means more cost-effective designs, which can start small in rivers to gain experience, and then be modified if necessary and scaled up to the point where they are suitable for large scale grid-connected tidal sites.

Available HKTs

Despite this obvious need, few if any HKTs are actually in rivers producing power. The literature abounds with optimistic articles about new HKT designs about to revolutionise hydrokinetic power supply.

Fig. 2. The 2 m diameter Mako axial flow turbine (https://www.mako.energy/technology).

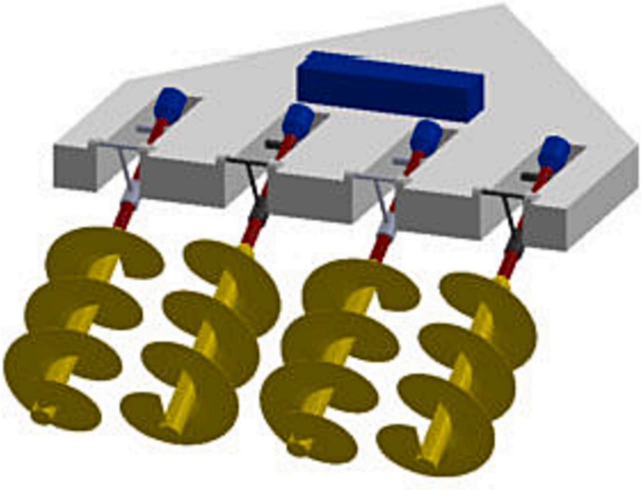

Fig. 3. Jupiter Hydro's Archimedean screw-type HKT concept (https://jupiterhydro.com/).

Most of these quietly disappear - Hydro Alternative Energy, UEK, Hydrogreen, Aquanator, Bluenergy, Free Flow Energy, Kobold, WPI, GHT, MCT, and Delta Stream to name but a few. According to Gary Brennan, Chief Technology Officer at GKinetic (Pers. Comm., 2023), Smart Hydro Power, apparently among the most successful listed in Table 1 above, have recently ceased production of their axial flow turbines, although they still have some stock for sale.

Among the few that are still in business as far as this author is aware, are four companies with very different products representing the main HKT types: axial flow, straight blade vertical axis, horizontal axis cross flow helical and Archimedean screw. No ducted axial flow turbines such as those produced by Guinard (https://www.guinard-energies.bzh/en/guinard-energies-2/) appear to be currently available on the market. A recent addition is GKinetic, an innovative vertical axis turbine.

Axial flow HKTs

The 2 m diameter Mako axial flow turbine, intended mainly for tidal flows, is claimed in Mako's website to be “Suitable for tidal flows, rivers, irrigation canals, and tailraces.” https://www.mako.energy/technology. However in 2020 it cost $20,000–70,000 (Tham & Lewis, 2020), which is very expensive for a 2 m diameter turbine, and it would require a large river with a depth well over 2 m (Fig. 2).

Archimedean screw-type HKTs

Jupiter Hydro's Archimedean screw-type hydrokinetic turbine is claimed by the company developing it to be the most cost-effective technology in the industry (https://jupiterhydro.com/). Shahsavarifard et al. (2015) have described tests on a small prototype turbine, which produced a performance coefficient C_P of about 0.45, which is impressive. No cost figures are given for this prototype, but it appears that the company is focused on Megawatt scale arrays, which it claims will cost 1/3 as much as the competition. According to https://jupiterhydro.com/, “The final pieces of the puzzle have only come together in the spring of 2023…” The unit shown in Fig. 3 below is a concept drawing of what they will design and build for deployment at their 2 MW site in the Minas Channel.

Vertical axis HKTs

New Energy Corporation

New Energy Corporation of Canada offer 5 and 25 kW vertical axis “EnviroGen” Systems, which according to their website have been installed around the globe. These are scalable with sizes from 5 kW ranging up to 250 kW. Fig. 4 shows their 1.5 m diameter model with 0.75 m long blades, designed to produce 5 kW in a 3 m/s current, requiring 1.4 m depth in its floating form or 1.22 m depth with fixed

Fig. 4. New Energy Corporation's 5 kW turbine on left, floating, on right, fixed mounting in partially blocked river (from https://www.newenergycorp.ca).

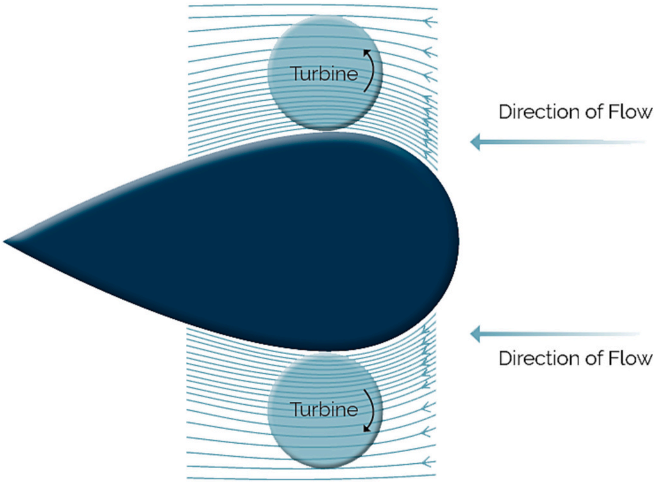

Fig. 5. GKinetic's concept, from https://gkinetic.com/technology/.

supports. They also offer a "low flow" 1.5 × 1.5 m option to produce 5 kW in 2.4 m/s flow velocity, requiring 2.15 m floating depth or 1.97 m with fixed supports. The required depth and current velocity to produce rated output mean it will only be suitable for very large, fast-flowing rivers as a floating HKT, but it may be suitable for smaller rivers where it can be mounted on fixed supports and most of the flow can be blocked, as shown in Fig. 4 (right).

GKinetic (Ireland)

According to their website, "The GKinetic concept involves two vertical axis turbines placed on either side of the buoyant vessel. The shape of the vessel increases the speed of water into the turbines. The combination of the accelerated flow along with our patented Blade Pitch Control System results in higher power outputs. Fig. 5 shows this concept schematically. It is claimed that "More power can be generated from slow-flowing water which is found in most deployment sites." But there is only a fixed amount of kinetic energy flux or power in a flow, and it is impossible to increase this except by a reduction in downstream level, i.e., by converting potential to kinetic energy. By accelerating flow around the obstacle, more of this energy is concentrated around the obstacle but the total is not increased. It is also claimed that this arrangement "naturally diverts objects away from the device."

According to GKinetic Energy CTO Gary Brennan (pers. comm), floating trees have been observed being diverted in a river in France, and "The specs of the device are 12kW, €78k and 1.9 ton." Again, this is a very expensive device that would require lifting equipment to deploy.

Horizontal axis cross-flow HKTs

ORPC (ORPC (Ocean Renewable Power Company), n.d.) (USA). Founded in 2004, ORPC has recently delivered its second RivGen device, a large submersible cross-flow helical turbine shown in Fig. 6, to the Village of Igiugig on the Kvichak River in Alaska (Garanovic, 2021). It is presumably designed to operate under the ice in winter. According to Thomson et al. (2014), describing the ORPC deployment site at Iguigig, "The mean flow in the center channel of the river is 2.5 m/s … with strong inflow velocity gradients across the turbine." Fig. 6 (right) shows velocities at points x and y, but it is not clear at what depth and in what season these readings were taken.

Despite the range of available HKTs, none is designed to develop rated power in flow velocities less than 2.4 m/s, nor are they suitable for operation in depths less than 1 m. Designers in high labour cost countries like the US, Canada and Germany are remote from third world users and have generally failed to design for real conditions. Their designs are typically expensive, bulky and difficult to deploy, and deliver far less than their rated power because they are designed for flow velocities far higher than those encountered in real rivers.

Diffusers

A diffuser on the downstream side of a turbine has the effect of reducing the pressure at the turbine exit, thereby drawing in flow from a greater area than the turbine's swept area and increasing the power output. An example is the DCO Sustentavel, n.d. (https://dcosustentavel.com.br), shown in Fig. 7. Because the diffuser has a greater diameter than the turbine itself, it increases the required depth, and the additional structure increases the cost and the likelihood of clogging by floating debris, so it is debatable whether there is an overall improvement in cost-effectiveness.

Low cost HKTs

Tan et al. (2021) reviewed available small HKTs and described a small-scale HKT prototype suitable for shallow rivers, designed and constructed from readily available off-the-shelf materials, costing less than USD 300 for the whole turbine excluding labour. It could be transported using a small pickup truck and produced 92 W of power

Fig. 6. ORPC's second RivGen device prior to installation at Igiugig, Alaska (Courtesy of ORPC) after Garanovic, 2022, and flow velocity at the site, after Thomson et al. (2014).

Fig. 7. The DCO Sustentavel HKT with diffuser. Generator installed above water level.

from a 1.26 m/s current velocity. Although this may seem insignificant, it has the potential to generate 2.21 kWh of energy daily with a steady 1.26 m/s current, which is sufficient for electrification of a household in a remote area to power-up several DC light bulbs and charge a battery bank. Although this was a prototype which will need some further development, it is an example of the sort of small HKT that can make a real difference in remote villages.

Components for the present prototype shown in Fig. 14 cost a little over AUD 1000 (USD 650). With a swept area of 2.16 m^2, about 8 times larger than that described by Tan et al. it should produce about 300 W in a 1 m/s current, assuming $C_P \sim 0.3$. Like the prototype described above by Tan et al., it will need some further development, but it is another example of the sort of small HKT that can make a real difference in remote villages.

Flow velocity and proximity to loads

Because power density increases with velocity v cubed, velocity is a crucial factor in site selection and turbine design. Designers have generally assumed flow velocities around 3 m/s, but as shown in Fig. 8, riverbed erosion increases steeply with velocity. A 1 m/s flow velocity near the stream bed will erode particles up to about 7 mm diameter, but the limit increases to 18 mm at 2 m/s flow and 55 mm at 3 m/s, and sandy riverbeds erode with higher velocities, leaving only rocky bottoms and the danger of turbine damage by rocks tumbling down the river during floods. It is therefore clear that 3 m/s is unrealistic, not only because it is extremely rare, but also for safety, and turbines should be designed for more common conditions, with overload protection like wind turbines. Turbines should be deployed in locations close to loads where V, and therefore power density, is maximum.

Fig. 9 shows a river in Sarawak, Borneo. In the foreground, right next to the village (not visible in the photo), the river is deep and slow, but a little way downstream where it crosses a rocky bar that will not erode it is much faster, and this is where a HKT should be placed, even allowing for a longer power cable to the village and a smaller flow area A. However, the water is shallower where it runs fast, as shown in Fig. 8, and there is insufficient depth for conventional turbines there.

Depth and flow area

As explained above, places with higher velocities generally coincide with shallow depth, as shown in Figs. 9 and 10, or they occur on the outside of bends where flow can be very non-uniform and difficult to locate turbines. The flow area intercepted by the HKT should be maximised for maximum power, and in shallow rivers this implies maximum width. A small diameter horizontal axis cross-flow turbine straight blade Darrieus or helical or possibly Savonius mounted with the axis of rotation across the flow, makes it possible to achieve a much larger swept area A than with an axial flow or vertical axis cross flow turbine, as shown in Fig. 11. Darrieus are preferred because Savonius rotors operate at lower TSR and therefore need more gearing to drive a high-speed generator. A long, small diameter helical turbine has a low helix angle and the inherent reduction in C_P due to the helix is less than with a steep helix angle.

Design for cost-effectiveness

Despite many publications assessing the potential for river hydrokinetic energy, and many companies that have set up optimistic websites but failed to deliver cost-effective systems, very few turbines are actually in rivers, generating useful energy. According to the US Department of Energy (DOE, 2020),

> *"Hydrokinetic energy is an abundant renewable resource that can boost grid resiliency and reduce infrastructure vulnerability, but it is currently a* ***cost prohibitive option*** *compared to other energy generating sources."*

They announced $35 million in funding for 11 projects to

> *"Develop new economically competitive Hydrokinetic Turbines (HKT) designs for tidal and riverine currents."*

AS mentioned in Costs and availability in 2019 section above, one of the companies receiving a $3.7 m share of this funding is ORPC (ORPC (Ocean Renewable Power Company), n.d., whose second RivGen device is shown in Fig. 6 prior to installation in Igiugig, Alaska).

> *"Projects will work to reduce the LCOE through multiple approaches, including increasing generation efficiency, increasing rotor area per unit of equivalent mass, lowering operation and maintenance costs, minimizing potential impacts on the surrounding environment, and maximizing system reliability."*

ORPC's RivGen is designed to operate at the bottom of the river. With such a large mounting structure in relation to the turbine swept area, it is difficult to see how they will reduce the cost significantly unless there is a radical re-design.

Power coefficient (performance coefficient) C_P

For a cost-effective hydrokinetic turbine (HKT), the power output per unit cost must be maximised.

Power $P = C_P \frac{1}{2} \rho A V^3$ where C_P is the power coefficient or performance coefficient, i.e., the ratio of power captured to kinetic energy flux through the turbine swept area A, ρ is water density, and V is the water flow velocity. Besides the factors determining power output, cost includes materials, fabrication, generator, gearing if necessary, power conditioning, transmission and battery or mains connection, transport to

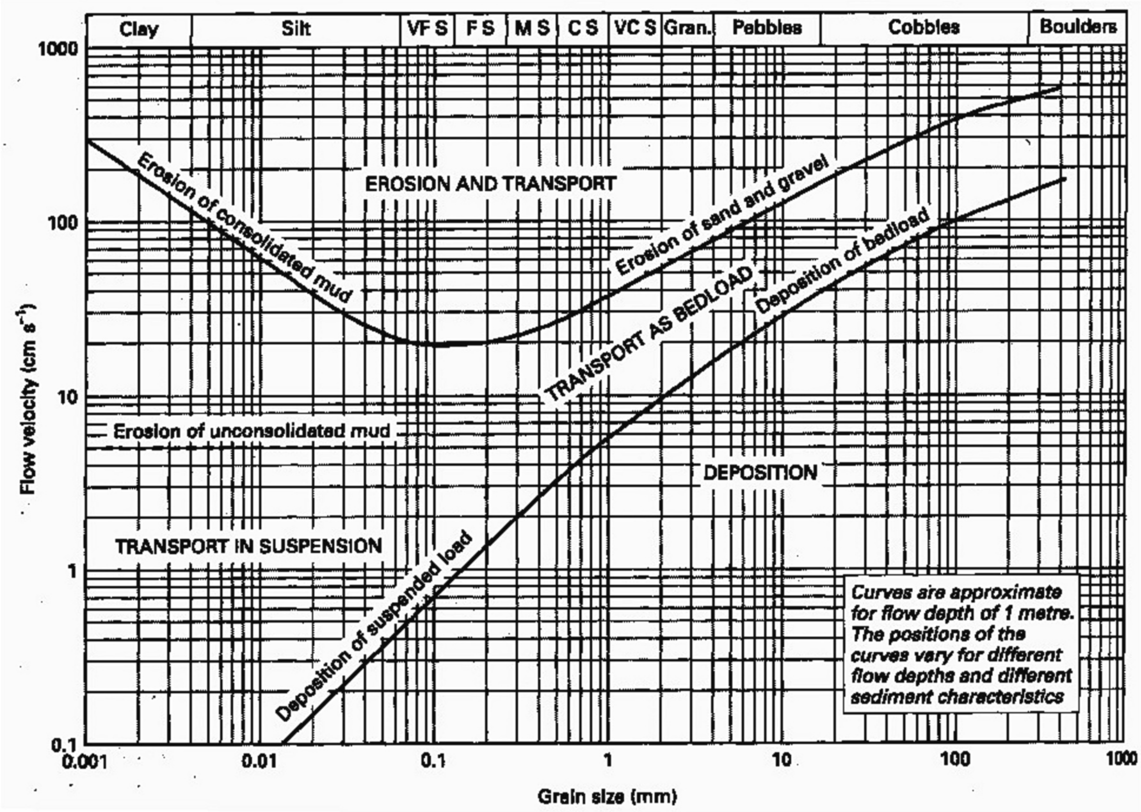

Fig. 8. The Hjulström-Sundborg diagram showing the relationship between particle size and tendency to be eroded, transported or deposited at different current velocities (Wikipedia, https://en.wikipedia.org>wiki>Hjulström_curve.

Fig. 9. The Engkari River at Long Anyat Village, Sarawak: flow in the foreground is deep and slow, downstream it is shallow and fast (photo by the author).

site, deployment and operation and maintenance.

The power coefficient or performance coefficient C_P is a measure of efficiency. C_P varies with turbine design, and one important factor influencing C_P for Darrieus-type turbines is solidity σ, normally defined as the ratio of blade area to swept area for axial flow turbines, and as nc/r for Darrieus turbines, where n = number of blades, c = blade chord length and r = turbine radius. As shown in Figs. 12 and 13, C_P also varies with

(i) tip-speed ratio λ, i.e., the ratio of blade tip speed to freestream water velocity v. For a turbine of any given solidity, there is an optimum λ for maximum C_P. As solidity increases, optimum λ and maximum C_P decrease (Fig. 12).
(ii) blade chord Reynolds number vc/υ, where υ = kinematic viscosity = 10^{-6} SI units approximately for water. Blades perform better at higher *Re* (Fig. 13).

It will be apparent from Figs. 12 and 13 that low solidity nc/r and

Fig. 10. A shallow, fast-flowing stretch in a river near Telinting in Sarawak where the outboard motor must be raised due to lack of depth and the boat must be pushed (photo by author).

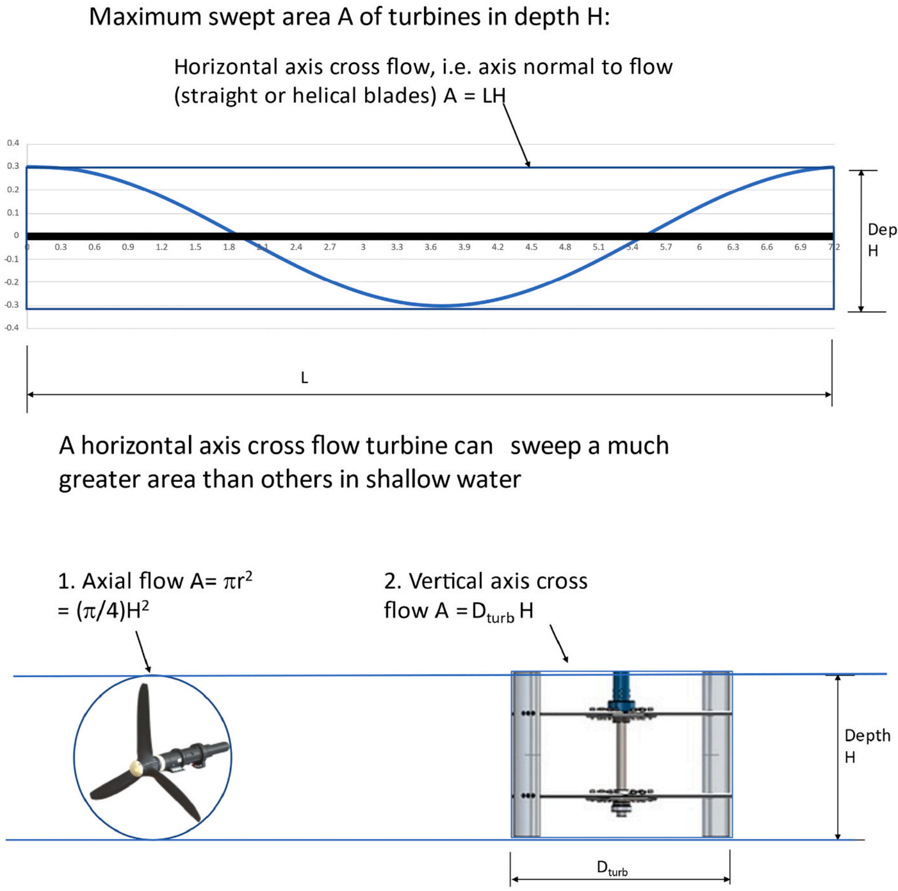

Fig. 11. It is possible to achieve a much larger swept area in shallow water with a long, small diameter horizontal axis **cross flow** turbine (upper image composed by the author) than with an axial flow or vertical axis cross flow turbine (lower image: Schottel axial flow turbine, n.d. image from Schottel, vertical axis turbine image from New Energy Corporation, n.d.).

high Reynolds number vc/υ are desirable, and these two requirements can be achieved with a small diameter, horizontal axis cross-flow HKT with a single blade at each cross section, as explained below.

Blockage and potential energy

The foregoing discussion applies to water turbines operating in "open flow," where there is plenty of space around the turbine for the flow to go around it. In such cases there is a theoretical upper limit to C_P

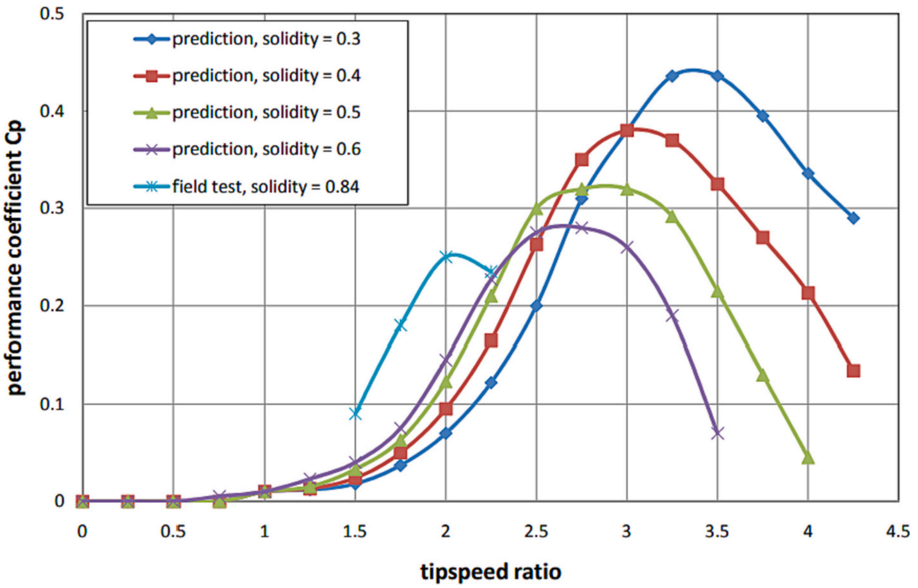

Fig. 12. High solidity reduces efficiency and the optimum tip-speed ratio of Darrieus turbines. After Kirke & Lazauskas, 2011.

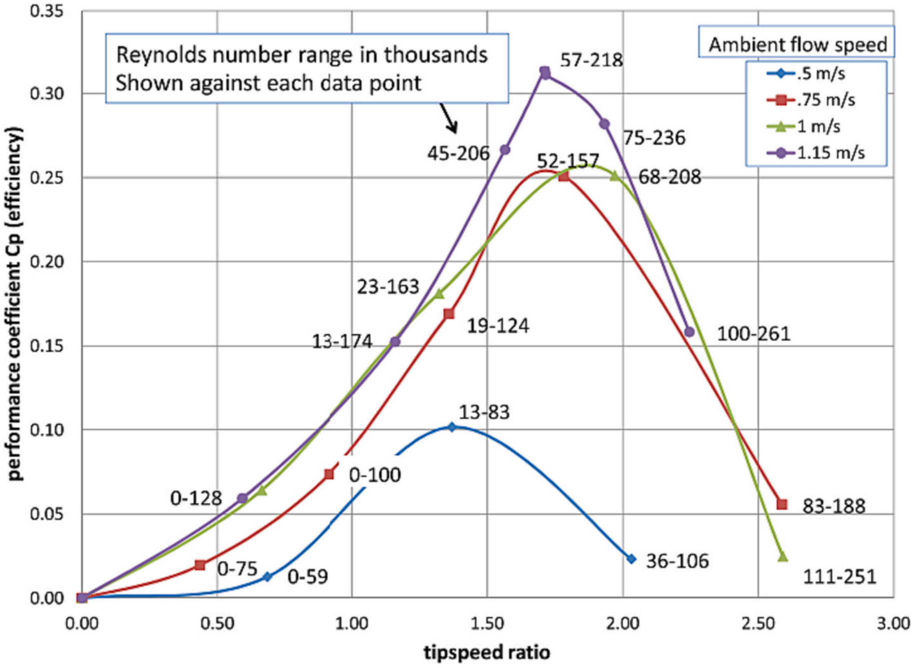

Fig. 13. The efficiency of a small Darrieus turbine at low blade chord Reynolds number *Re* is very sensitive to *Re*. (Note also that *Re* is much larger when a blade is moving upstream than when moving downstream at low tip-speed ratio λ). After Kirke, 2016.

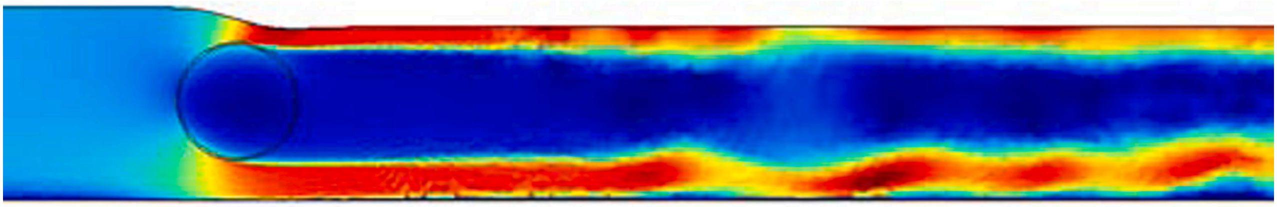

Fig. 14. Modelled velocity contour plot with a blockage of B = 0.625, Froude number 0.19 and free surface deformation. Flow from left to right. High speed flow regions are shown in red and low speed regions in dark blue. The turbine is represented by the circle on the left. After McAdam et al., 2013.

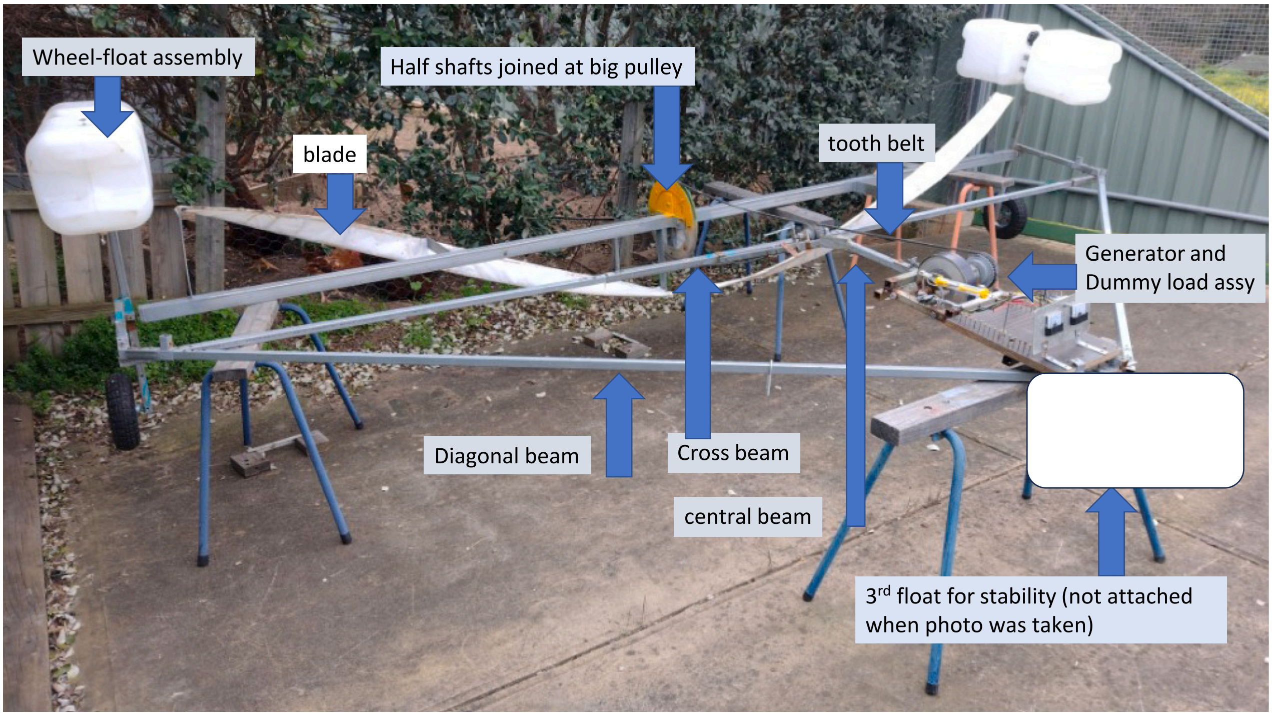

Fig. 15. A prototype 0.6 m dia, 3.6 m long single sail helical turbine (3rd float for stability not shown).

of 16/27 or 59.3 %, called the Betz limit, also called the Lanchester–Betz or the Betz–Joukowsky Limit. But in relatively small waterways where a turbine takes up a significant portion of the flow area, it is more difficult for the flow get around, so the upstream water level rises slightly, there is a 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 these are "zero head" turbines.)

The increased power from a "hydrokinetic" turbine with blockage was illustrated by measurements in a laboratory flume by McAdam et al. (2013). They found that a Darrieus turbine that would have achieved C_P no more than about 0.3 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, and the modelled velocity contour plot, Fig. 14, shows that this was indeed the case.

In fact, the drop in surface level downstream shows that the *average* kinetic energy flux actually **increased downstream** due to accelerated flow above and below the turbine, although it was slowed immediately downstream of the turbine. So the term "hydrokinetic" is not strictly correct, and the turbine would be better described as "ultra-low head,"

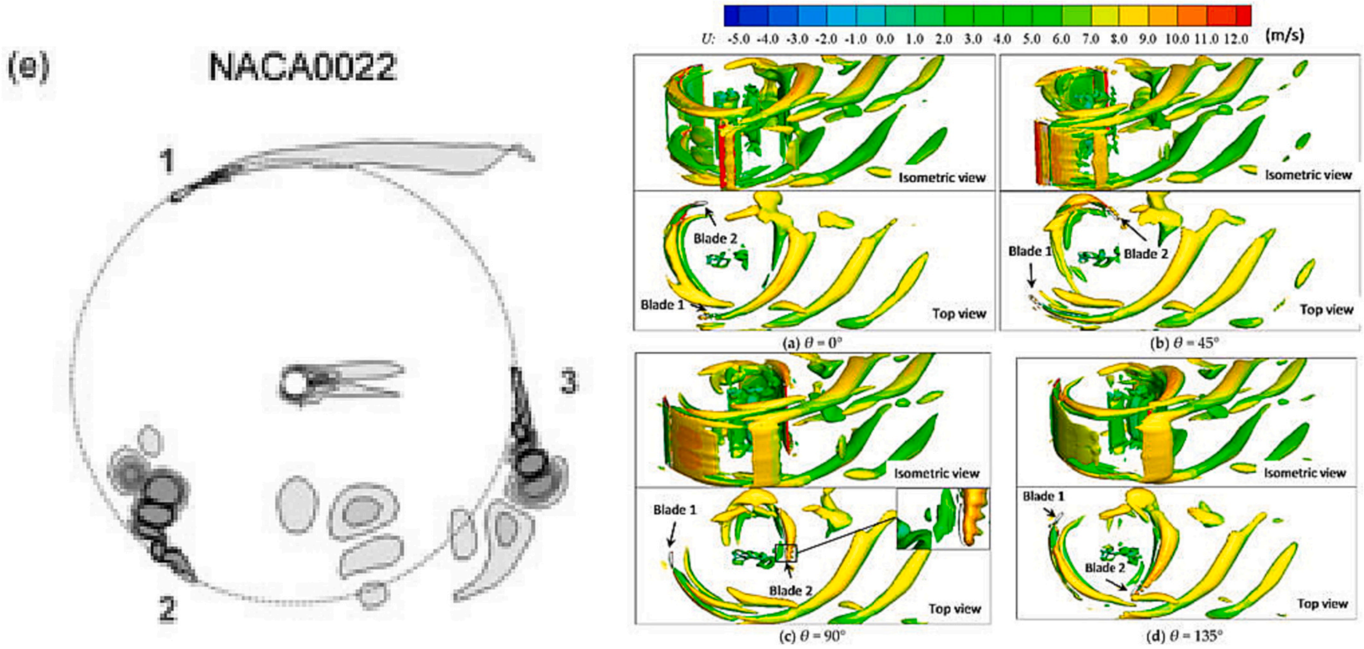

Fig. 16. Vortex and wake shedding visualisation (Left) at λ = 2.75, after Danao et al. (2012), and (right) after Yang et al. (2017).

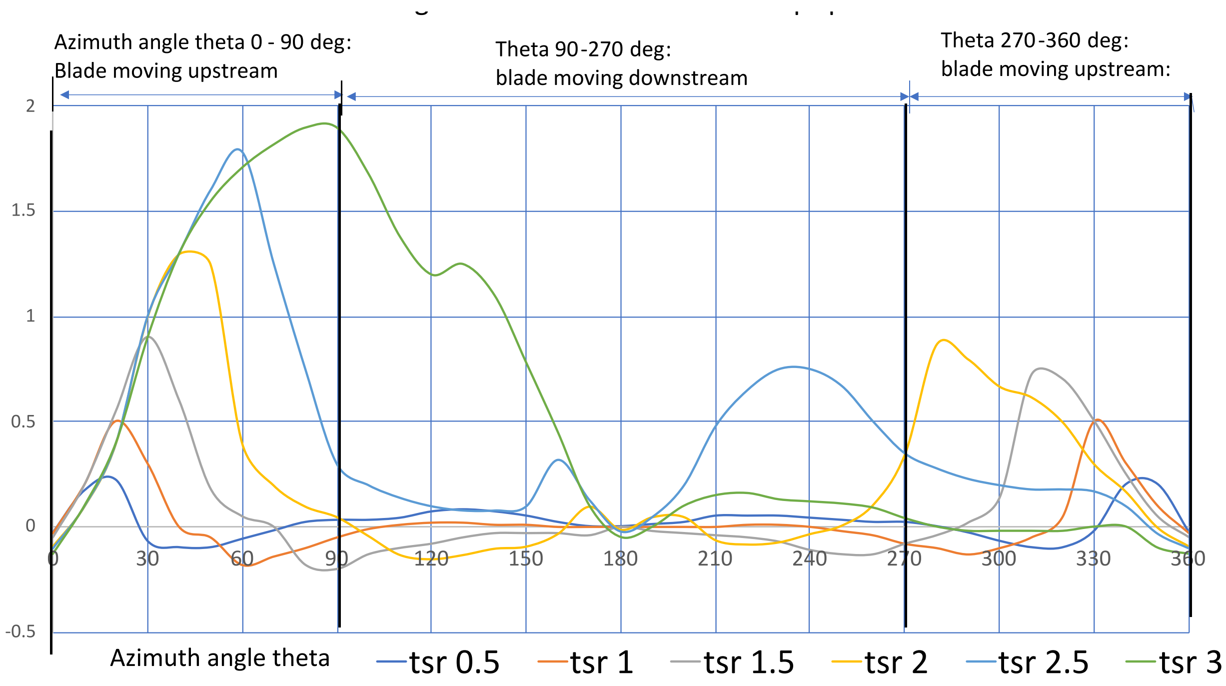

Fig. 17. Nondimensional tangential force F*T vs. azimuth angle for tip-speed ratios from 0.5 to 3. Most of the tangential force and therefore power is produced on the upstream pass (based on Lazauskas, 2008, Kirke & Lazauskas, 1993).

although the term “hydrokinetic” is still used loosely to describe any turbine where not all of the flow is forced through it. Fig. 4, right, shows New Energy Corporation's standard Darrieus turbine in a near-fully blocked arrangement, where some potential energy or “head” is clearly involved.

Advantages of a single flexible blade helical turbine

Besides the advantage mentioned in Design for cost-effectiveness section and illustrated in Fig. 11, i.e., (i) greater swept area in shallow water than axial flow or vertical axis HKTs, (ii) low solidity and high Reynolds number, a further advantage is that tethers attached at each end of the shaft of a horizontal axis cross-flow HKT virtually eliminate the overturning moment of the downstream drag force on the rotor which in conventional vertical axis HKTs is balanced by a large, expensive pontoon mounting structure like that shown in Fig. 4(Left). In contrast, the helical turbine shown in Fig. 15 requires only three small floats for buoyancy and stability, three legs to prevent the rotor hitting the bottom in times of low water level, and a tether. Fig. 15 shows a prototype 0.6 m diameter, 3.6 m long helical turbine with a single flexible fabric blade or sail in place of a rigid blade, designed to operate fully submerged in depths less than 0.8 m, or part-submerged in even shallower water (see Figs. 16, 17).

The leading edge of the helical blade was formed by bending two 2 m lengths of 12 mm diameter steel rod around a 600 mm diameter x 1.8 m long surface formed by two half 200 L drums placed end to end. Each 2 m length made half of a complete 360° helix at 30° to the axis of rotation. The trailing edge was then formed by a 12 × 3 mm flat steel bar, connected to the leading edge by welding 100 mm long pieces of 12 × 3 mm steel at intervals. Sailcloth was then wrapped around the leading and trailing edges with enough slack to enable a camber to form. The helix was fixed by 275 mm long radial arms of 50 × 3 mm steel at 0.9 m

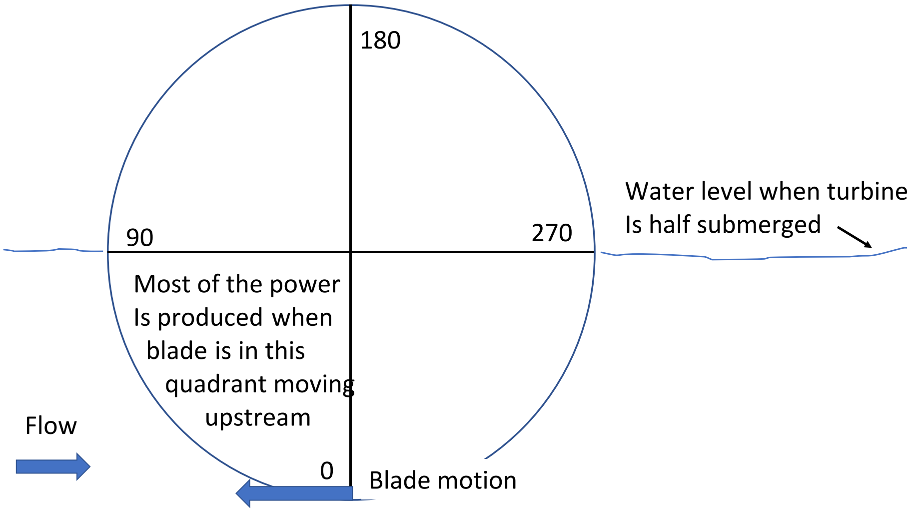

Fig. 18. Half-submerged turbine rotation with submerged blades moving upstream.

Fig. 19. Debris accumulation on a pontoon-mounted HKT in Alaska (after Tyler, 2011).

intervals to a shaft of 2 lengths of 50 × 50 × 1.6 mm galvanised square hollow steel each 1.8 m long, mounted end to end and bolted to a 340 mm diameter tooth belt pulley at the midpoint. This provided a 3.4:1 step-up gear ratio to a 100 mm pulley on the generator, a Windpmg brand low speed 3 phase generator (windpmg.com) connected to an adjustable resistive dummy load. The shaft was mounted in bearings at each end, with a float on an upright for buoyancy and a wheel for easy launching. A third float, not attached at the time the photo was taken, was provided for stability.

This turbine was a work in progress and failed to self-start under load, possibly because (i) the sail material was not slack enough to form a cambered profile that would reverse with reversal of incidence, (ii) the short chord length corresponds to low *Re* and low C_P (Fig. 12), and (iii) the semi-circular leading-edge profile would cause stall at a low angle of attack, as discussed in detail in Kirke and Abdolahifar (2023). A new prototype has been constructed, with larger chord and more attention paid to slack and leading-edge profile, and is awaiting suitable weather and availability of the towing vessel for testing.

Summarising the advantages of a helical turbine with a single flexible blade or sail as shown in Fig. 15 over one with 2 or more blades or sails or a straight blade Darrieus:

(i) Higher efficiency due to higher Reynolds numbers for the same solidity, as shown in Figs. 12 and 13.
(ii) Less fabrication, making HKT cheaper and simpler.
(iii) Blades can be nested for compact, easy transport.
(iv) Fewer radial arms than necessary for multiple straight blades, so less parasitic drag loss

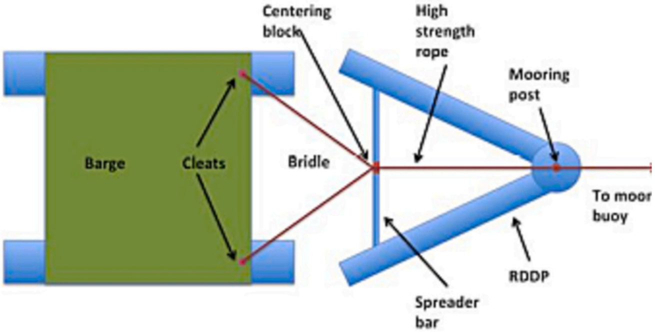

Fig. 21. Mooring configuration of the test barge and research debris diversion platform (Johnson et al., 2015).

(v) Only one blade per revolution passing upstream and generating turbulence which may impact blade on downstream pass (Fig. 16).
(vi) A flexible sailcloth foil behaves a bit like a yacht sail when tacking, with the belly (i.e., camber) reversing as the yacht goes about and the angle of attack reverses, and modelling based on published lift and drag data indicate that torque and C_P are higher for a turbine with flexible blades than a comparable turbine with rigid NACA0018 or Goe 420 blades (Kirke & Abdolahifar, 2023).
(vii) Sailcloth or flexible PVC sheet is inexpensive compared with blades made of fibreglass or extruded or NC-milled aluminium.

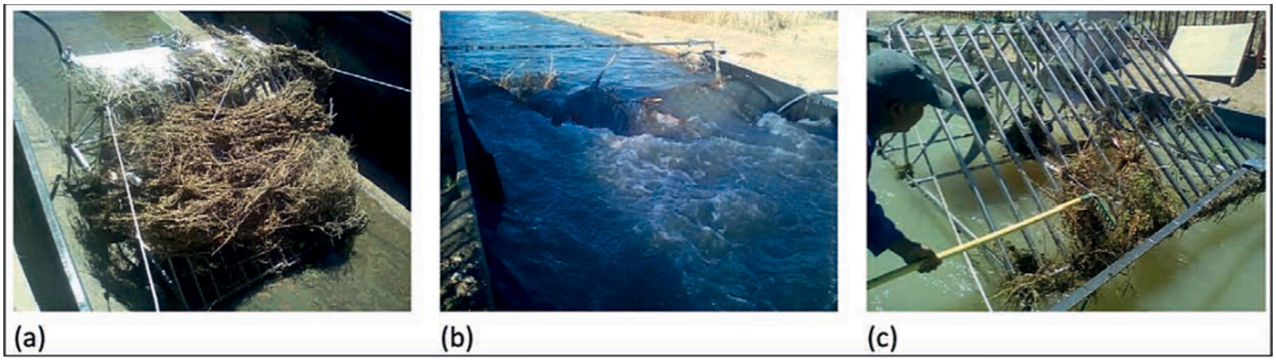

Fig. 20. Debris blocking a pair of Smart Hydro turbines in South Africa (Niebuhr et al., 2021).

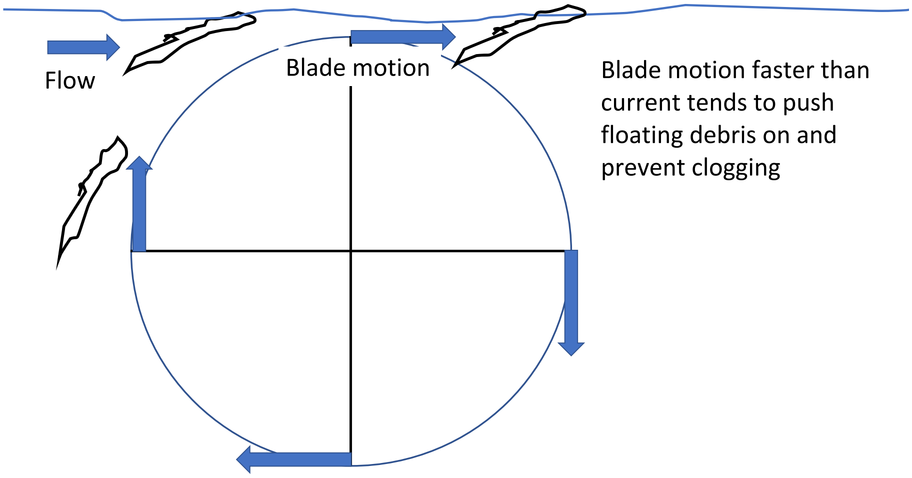

Fig. 22. Blade motion to avoid clogging by small floating debris.

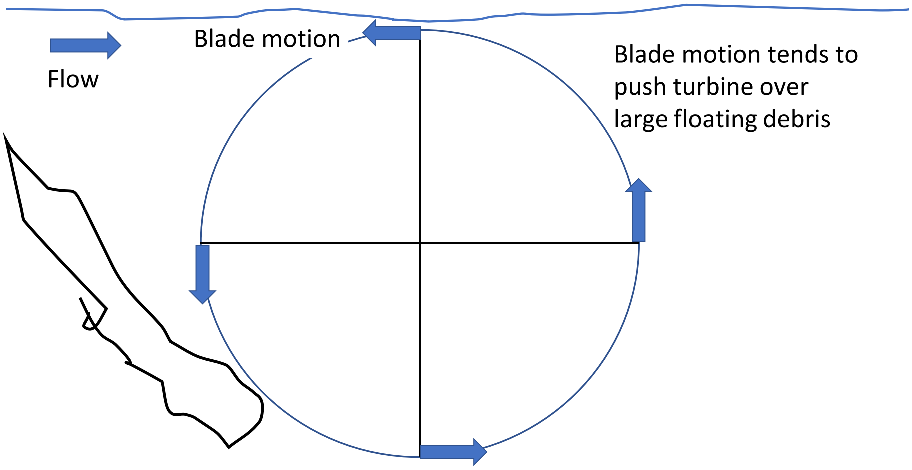

Fig. 23. Alternative blade motion to ride over large floating debris.

Operation part-submerged

A horizontal axis cross-flow turbine will operate satisfactorily part-submerged, provided it is rotating with blades moving upstream at the bottom of their travel, where most of the tangential force and therefore power is produced, as shown in Figs. 17 and 18.

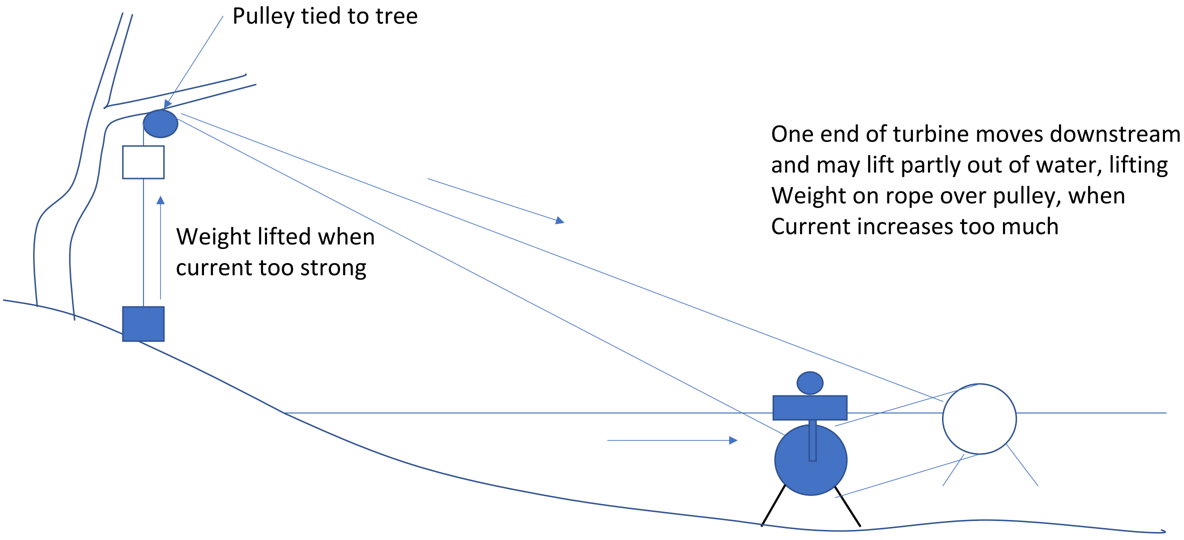

Fig. 24. Overload control.

Blockage by debris

A major problem with HKTs is blockage by debris. Fig. 19 shows debris accumulation on a pontoon-mounted HKT in Alaska, and Fig. 20 shows two 1 m diameter Smart Hydro turbines with a grid of bars intended to prevent debris buildup, which was apparently ineffective as it needed cleaning at 2-week intervals.

Fig. 5 shows GKinetic's design which is claimed to deflect debris, and Fig. 21 shows Alaska Hydrokinetic Energy Research Center's "research debris diversion platform" (RDDP), which "consists of two pontoons connected at their upstream end by hinged pins that allow adjustment of the separation angle between the pontoons using a hydraulic pump. A debris sweep, consisting of a cylinder that is free to rotate in clockwise or counterclockwise directions, was placed in front of the pontoons to prevent debris from catching on the front of the RDDP. … all surfaces that come into contact with debris are covered with low-friction material." It is claimed that this rather elaborate device was effective and was a significant improvement on earlier models (Johnson et al., 2015).

The HKT shown in Fig. 15 was designed so the blade moves downstream on its upper half revolution so as to propel debris **over** the rotor and downstream, hopefully avoiding clogging (Fig. 21). However Dr. Martin Anyi of Sarawak Energy Berhad (pers. comm.) argues that it is better to tether the HKT to fixed points well above the water surface and design it so the blade moves upstream on its upper half revolution and climbs **over** the debris (Fig. 22). Although the advantage of part-submerged operation is then lost, this appears a better arrangement (Fig. 23).

Overload control

Small wind turbines and pumping windmills are designed to yaw in strong winds so as to present less swept area to the wind. The same can be done with horizontal axis cross flow turbines by tethering one end to a dead weight (Fig. 24) or a preloaded spring so that it moves downstream when the current velocity exceeds that required for rated power and returns to normal operating position when the current velocity subsides to a safe level. Alternatively, the vertical component of tension on the tethers may be designed to overcome its submerged weight when the current velocity reaches a design level, so the rotor lifts partially or completely out of the water, reducing or eliminating the swept area and load, and protecting the turbine from damage.

Conclusion

A horizontal axis helical cross flow hydrokinetic turbine (HKT) with a single blade of flexible material between rigid leading and trailing edges is proposed for shallow rivers. Such turbines are able to sweep a larger area and generate more power than axial flow or vertical axis turbines in the high velocity, shallow reaches of rivers. Darrius turbines are preferred to Savonius rotors or paddle wheels as they work at higher tip-speed ratio and so require less gearing to drive a generator. Helical blades spanning the full 360 degrees of azimuth angle eliminate torque ripple, and a long, small diameter turbine with a single blade can span 360° with a small helix angle, which minimises the loss of efficiency inherent in helical blades. There will be some shaking due to unbalanced radial forces along the shaft, but they even out over the full 360°. A single blade on a small diameter turbine can achieve a good combination of high Reynolds Number and low solidity for high efficiency. A single blade requires less fabrication than multiple blades, making it cheaper and simpler. One blade per revolution passing upstream and shedding turbulence may have minimum impact on the blade on its downstream pass, and fewer radial arms minimise parasitic drag loss. Flexible blades are cheaper than rigid blades and are predicted to generate more power and starting torque. Single blade turbines can be easily nested for transport, in contrast to the normal 3 blade designs.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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