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Hydrokinetic Energy Conversion Systems and Utilization of River Current for Electricity Generation

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Abstract:
The growing demand for electrical energy is one of the most important challenges that the world is facing today. Hydrokinetics studies how kinetic energy is generated by the natural movement of water-river and streams currents and how to convert that energy to electricity. Hydrokinetic energy, the power of moving water, is a promising new, vast, and renewable resource of energy. To tap this source of hydropower, in-stream water current or kinetic energy turbines are deployed. These turbines generate power from the kinetic energy of a flowing stream of water without the use of a dam or barrage structures. Hydrokinetic devices are placed directly in the flow and generate energy only from the power of the moving water. Water current turbines can be installed in any flow with a velocity greater than 1.5 m/s. Because of low investment costs and maintenance fees, this technology is cost effective in comparison to other technologies. The continuous supply of electrical energy is also an advantage in comparison to solar power or other small-scale renewable technologies. This kind of small-scale hydropower is considered environmentally friendly, meaning that the water passing through the generator is directed back into the stream with relatively small impact on the surrounding ecology. Due to the low cost and durability of this kind of hydro-power systems, developing countries can manufacture and implement the technology to supply the needed electricity to small communities and villages. Systems can be installed in isolated or grid connected configurations, stand-alone or as a supplement to existing generators, floating or fixed to the bottom of a water course. Since many remote communities are situated near moving water these turbines represent a promising source of clean power. Kinetic energy turbines represent a significant yet untapped source of hydropower from South Africa’s and Botswana’s abundant water resources.
This paper gives detailed information about current base of hydrokinetic energy for river application and power generation. Applications in free-flowing rivers and reviews of some of the existing turbine technologies are outlined. In addition to that, it has tried to give a future concept about suitable turbines for river currents and implementation challenges.

Keywords Hydrokinetic energy; hydrokinetic river technology; Renewable energy; Fossil fuels; Environmental effects, Rural electrification

1. Introduction

The need for alternative methods in how we generate power has become increasingly apparent given the role of fossil fuels, climate change and the rate at which those fuels are being depleted. With this understanding has come the development of many forms of renewable energy. One such promising candidate is hydrokinetic energy. This is a growing field within renewable energy i.e., conversion of hydrokinetic energy into electricity that employs turbines. This class of technologies are designed to take advantage of this yet untapped energy source Hydrokinetic energy which is a promising new technology still in the research and development stages [1].

Hydrokinetic power refers to the generation of power from the flow, currents or velocity of water. Since hydrokinetic power relies simply on the velocity of water, the systems can be placed into sources of flowing water with minimal infrastructure or changes to the environment.

The term ‘Hydrokinetic Turbine’ has long been interchangeably used with other synonyms such as, ‘Water Current Turbine’ (WCT), ‘Ultra-low-head Hydro Turbine’, ‘Free Flow/Stream Turbine’ (implying use of no dam, reservoir

or augmentation), ‘Zero Head Hydro Turbine’, or ‘Instream Hydro Turbine’, Current Turbine’. For rivers or artificial waterways, the same technology is generally identified as ‘River Current Turbine (RCT)’, ‘River Current Energy Conversion System (RCECS)’, ‘River In-Stream Energy Converter’ (RISEC), or in brief, ‘River Turbine’.

Hydrokinetic power offers renewable energy with no pollution or emission of greenhouse gases [1-5]. Hydrokinetic power also has the advantage of being predictable and is often available for 24 hours a day, allowing for high-capacity factors – potentially as high as 98% of the year for instream. The disperse nature of hydrokinetic power allows generation at levels ranging from diesel replacements and distributed power to utility scale power.

Worldwide, there is great interest in the potential for hydrokinetic power to serve as a substantial new source of clean, reliable and renewable energy. And a hydrokinetic power industry is starting to emerge in several countries. Hydrokinetic power holds great promise as a new, carbon-free, domestic energy source [6-16].

Most important, the robust development of a hydrokinetic power industry will increase the South Africa’s and Botswana’s ability to combat climate change, reduce the use of fossil sources for power generation, reduce harmful air emissions and help meet the world’s growing demand for new electricity in an environmentally responsible manner. South Africa and Botswana largely depends on coal for its electricity generation.

In-stream water current or kinetic energy turbines represent a new power generation market segment, capitalizing on the kinetic energy in a flowing stream of water [17-20].

Utilizing the energy in a flowing stream of water without the need for dams or diversions represents a clean sustainable economic alternative power generation source in many locations where no such option presently exists or where additional generation from clean sources is desired.

This technology have a bright future in both the stand alone and grid connected applications for distributed or centralized power production, and are yet another tool to add to the mix of renewable energy options available where suitable water resources exist. These resources range from small rivers and man-made water courses that can be used to power a residence, resort, or small community particularly in rural areas that lack national grid connections. Hydrokinetic energy systems options can either be stand-alone or grid connected and ultimately can be utilized to make a significant contribution to overall power generation capacity.

The uses of kinetic energy of water current for generating electricity or pumping has been studied for a long time, which mainly aims to use in remote areas [21-41].

2. Types Hydropower Plants

Various Hydro-power plants have been used to produce electricity from water. These include:

Conventional hydroelectric plants harness the potential energy stored in large reservoirs creating a hydraulic head differential which is converted to electrical energy through one or more large turbine/generator systems. These plants can produce power levels in the GW range and have the advantage of storing sufficient water volumes to maintain flow rates and thus power generation capability that can be managed over longer periods of time minimizing the impact of short-term flow events.

Run-of-river hydro plants on the other hand typically divert only a portion of the river flow for use in the plant. A head pond is used to maintain a consistent water level for the intake and to ensure the penstock is fully submerged, but the plant does not store large quantities of water. Instead, the natural elevation change in the river or stream is utilized to provide the necessary head to drive a turbine located in the powerhouse below. Typically, these plants generate power in the tens of MW range but are subject to restrictions in the water they can use and are more prone to variations in river flow.

In-stream water current or kinetic energy turbines go one step further by simply utilizing the energy in the velocity of the water in the stream i.e. the kinetic energy is generated by the natural movement of water. A small static head differential can also be created across the turbine to enhance the velocity where native water velocities are too low for practical energy extraction, but this differential is generally limited to less than 2m due to cavitation concerns. Clearly the energy densities associated with this type of turbine are much less than that of a high head hydro dam. However they do represent an economical and environmentally friendly means of power generation in locations where traditional forms of hydro generation are not possible (due to a lack of elevation change or other practical considerations). Power output of these turbines ranges from a few kW for a small turbine in a stream to installations in larger rivers that can produce several hundred kW to several MW.

3. Moving Water As A Source Of Energy

A river current energy conversion system can be described as an energy converter which harnesses the kinetic energy of river streams.

Hydrokinetic devices are powered by moving water and are different from traditional hydropower turbines in that they are placed directly in a river current. They generate power only from the kinetic energy of moving water (current). This power is a function of the density of the water, cross-section of flow that can be intercepted and the speed of the current cubed. The available hydrokinetic power depends on the speed of the river or stream currents.

The basic equation for instantaneous power availability is expressed as:

$$P = \frac{1}{2}\rho A V^3 \qquad (1)$$

where: P is the power removed from a stream of water current, V (m/s) is the undisturbed instantaneous point velocity of the oncoming flow in the cross-section or the free-stream velocity at hub height at the location of interest [42], ρ is the density of the fluid.

Fresh water has a density of 1000 kg/m^3 at 5°C [43]. A is the cross-sectional area of the hydrokinetic device that perpendicularly intersects the oncoming flow and V is the free-stream velocity at hub height at the location of interest. In the above equation, A and V are the only two variables that determine power and hence energy availability (energy being the integral value of power with respect to time) where A is technology specific and V is site specific. The main point to note is that, all other things being equal, the swept area of flow intercepted dictates how much energy can be captured. The area of current cross-section intercepted is critical. The more swept area the more energy can be captured.

As power is proportional to the cube of the velocity, it is of particular interest to identify zones within a waterway that provide high velocities and sufficient depth to accommodate a device. The proper identification of sites will allow for the optimal functionality of devices and determine the economic viability of a project, which is dictated by the power density at a site. To locate sites with the greatest potential, it is important to understand the complexities that characterize rivers.

The speed of a river varies from close to 0 m/s to 3.1 m/s. Factors that affect the speed of a river include the slope gradient, the roughness of the channel, and tides. Rivers tend to flow from a higher elevation to a lower elevation. The gradient is the drop of the elevation of a river. Therefore, the rivers speed is at its maximum at the headwaters (high gradient, high energy) and at its minimum at the base level (no gradient, lowest energy).

The further key factor that also influences energy capture is the efficiency of energy conversion; different devices and power transmission systems can have significantly different levels of efficiency. Rotor efficiency is conventionally defined as the percentage of shaft power produced by a kinetic energy converter of the power in the undisturbed upstream flow passing through an area equal to the cross section of flow intercepted.

The maximum theoretical efficiency of an ideal kinetic energy converter in a free stream (i.e., where the flow is uniform and the flow boundaries are far from the rotor) is 59.3%, a realization generally attributed to Betz [44,45]. This is because if the device took out 100% of the energy, the flow would obviously stop, so sufficient residual kinetic energy is required to carry away the flow after it passes through the device. This so called Betz limit defines the optimum arrangement where the flow downstream of the rotor is reduced to 1/3 of the original flow velocity at which point energy conversion is maximized.

In practice imperfections in the conversion mechanism results in a lower efficiency than the Betz Limit. The best modern wind turbines typically can touch about 50% peak efficiency and generally achieve efficiencies in the upper 40s (i.e. 75 to 80% of what is theoretically possible). The losses are largely due to a combination of friction and form drag (i.e. losses inherent in moving something fast through a fluid caused by stirring the fluid and resulting friction losses). Further losses, mechanical and electrical, occur between the rotor and the grid connection.

As mentioned in the above introduction, hydrokinetic devices require a minimum current and water depth. The minimum current required to operate a hydrokinetic device is typically 2-4 knots. Optimum currents are in the 5-7 knot range. Water depth is an important factor in the total energy that can be extracted from a site since rotor diameter is dependent on adequate water level above the installed device. Hydrokinetic devices are ideally installed in locations with relatively steady flow throughout the year, locations not prone to serious flood events, turbulence, or extended periods of low water level.

4. Hydrokinetic Energy Potential In South Africa And Botswana

Vast amounts of untapped energy remain in the numerous rivers across South Africa and Botswana [46]. Thousands of Kilowatts of energy continuously flow down rivers and streams in South Africa and Botswana, just to dissipate. Both countries have significant potential for hydrokinetic development in rivers and river basins. Most inland communities in South Africa and Botswana are situated along navigable waterways that could host hydrokinetic installations and could be one of the emerging homes to some of the best hydrokinetic energy resources. For river hydrokinetic energy, small, medium and large inland rivers such as the Zambezi, Limpopo, have promising potential power. Hydrokinetics can largely be tapped resource with no shortage of sites where significant amounts of power could be efficiently extracted, refer to river maps of South Africa and Botswana (Figures 1 and 2), which according to the author are potential sites.

Figure 1 South Africa River map

Figure 2 Botswana river map

This potential has accelerated research in the field of hydrokinetics, the science of understanding how to convert the kinetic energy in moving water of rivers and streams into electricity. Green Energy Solutions (GES) Research Group, headed by the author is pursuing research in development, modelling and implementation hydro-kinetic energy systems.

5. Prospects And Merits Of Hydrokinetic Energy

The demand for cheap and environmentally friendly source of energy is expected to increase significantly.

5.1. Rural electrification in developing countries

It is believed that many developing countries such as, China, India, Brazil and South Africa will appear as the key drivers behind the boost in energy demand in future. Over 2 billion people have zero access to electricity, 1 billion people adopt mundane power sources (dry cell batteries, candles and kerosene) and 2.5 billion people in developing countries, mainly in rural areas, have marginal access to national electricity grid. Such a contrast implies an acute need for suitable energy option for rural areas in the developing world. Historically, rivers have played a paramount role in shaping and sustaining civilizations. Most of the populous areas in the world have a river in their proximity providing a source of fresh water, food and transportation. Many developing countries are crisscrossed with rivers carrying significant volume of water round the year. An effective and low-cost mechanism for harnessing energy from the flowing river may revolutionize the scenario of rural power generation. A brief look at the world atlas reveals an interesting correlation between populations, need for electrification, poverty and river distribution. This match is more dominant in Asia, Central Africa and South America. A detailed quantitative analysis with global perspective may point to significant socioeconomic importance of river as a source of energy.

5.2. Impact on environment

Hydrokinetic energy systems could be used as distributed systems installed over a large river basin area. Therefore, environmental adversities attributed to this kind of technology are expected to be minimal for the proposed case. However, a thorough investigation on turbine usage and its effect on natural flow of the river, impact on river course, ecosystem, and wildlife would only reveal the true extent of such assumption.

5.3. Use of available technologies

Most of the components (blade, generator, power converter, etc.) needed for designing a turbine system are mostly readily available. Therefore, product development cycle, cost and level of technical sophistication are expected to be low for this technology.

5.4. Minimal need for civil engineering work

River turbines are generally being proposed as modular and small power sources placed close to the end user. Subsequently, the need for civil engineering work would be minimal compared to conventional large and micro hydroelectric systems, where the construction of dams and waterway consumes significant resources.

5.5. Unidirectional operation and less flow variation

Unlike wind energy, river flow is more predictable and flow variation is in the interval of hours or days. Therefore, the need for fast acting control and protection method is less stringent. Wind direction sensing and turbine alignment is a must for wind turbines. In contrast, water flow in a river is unidirectional and placement of a turbine with fixed orientations would suffice most applications.

5.6. Use of channel augmentation

Channel augmentation schemes concentrate the flow of fluids around a turbine and permit higher level of energy extraction. Although, sound in principle, applications of such devices were not successful in wind turbines owing to many practical challenges such as, tower-head placement, variable orientation, weight and size. Channel augmentation in river turbines appears more suitable as it needs no change in direction, could be placed under water and the structure itself may work as a flotation device.

5.7. Noise and aesthetics

Underwater installation of a turbine, away from public places would cause no noise disturbance and have zero visual impact. Unlike large hydro systems, impact on river navigation, swimming and boating is expected to be minimal.

5.8. Diversity of application

Electricity production would be the foremost choice of application for a River Current Energy Conversion System (RCECS). Depending on the availability of a power grid, stand-alone or distributed power generation schemes could be adopted. These turbines could potentially provide several services such as, water pumping for storage, livestock, human consumption, small industry and irrigation. In such applications, water pumps could be employed instead of electrical generators, to facilitate direct mechanical energy conversion.

5.9. Appropriate technology

River Current Energy Conversion Systems can be possibly built, operated and maintained using local resources and skills. With proper low-tech design and financing mechanism, such turbines may appear as appropriate technologies in developing countries.

6. Conversion Schemes And Operation

Khan, et al has extensively studied and reviewed Kinetic energy conversion systems [56]. The two most common developed small-scale hydrokinetic turbine concepts are: Horizontal axis (axial flow) turbine and crossflow turbine. Based on the alignment of the rotor axis with respect to water flow, three generic classes could be formed (a) horizontal axis, (b) vertical axis, and (c) cross flow turbines.

6.1 Horizontal axis (axial-flow) turbines

These have axes parallel to the fluid flow or incoming water stream and employ propeller type rotors. Various arrangements of axial turbines for use in hydro environment are shown in Figure 3. Inclined axis turbines have mostly been studied for small river energy converters. Literature on the design and performance analysis could be found in [47,48,49].

Most of these devices were tested in river streams and were commercialized in limited scales. The turbine system reported [50-52] were used for remote area electrification. Turbines with solid mooring structures require the generator unit to be placed near the riverbed or seafloor. Reports and information on rigidly moored river turbines are available in [53-55]. Horizontal axis rotors with a buoyant mooring mechanism may allow a non-submerged generator to be placed closer to the water surface. The cross flow turbines have rotor axes orthogonal to the water flow but parallel to the water surface.

6.2 Vertical axis turbine

These have axis vertical to the water plane, types of which are given in Figure 4 [20]. In the vertical axis domain, Darrieus turbines are the most prominent options. Although use of H-Darrieus or Squirrel-cage Darrieus (straight bladed) turbine is very common, examples of Darrieus turbine (curved or parabolic blades) being used in hydro applications is nonexistent. The Gorlov turbine is another member of the vertical axis family, where the blades are of helical structure. Savonious turbines are drag type devices, which may consist of straight or skewed blades. Hydrokinetic turbines may also be classified based on their lift/ drag properties, orientation to up/down flow, and fixed/variable (active/passive) blade pitching mechanisms. Different types of rotors may also be hybridized (such as, Darrieus–Savonious hybrid) to achieve certain performance features.

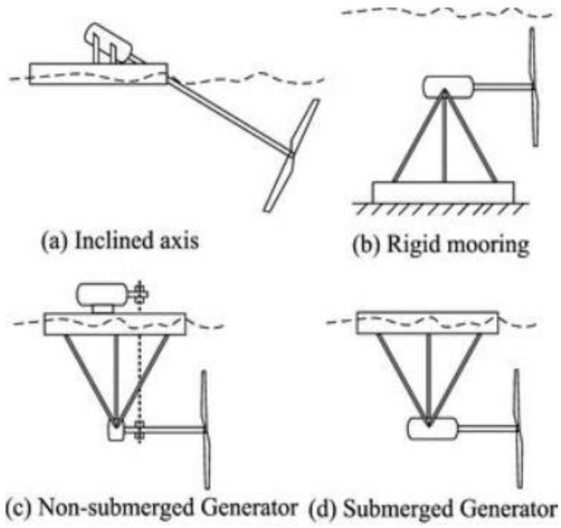

Figure 3 Horizontal axis turbines [20]

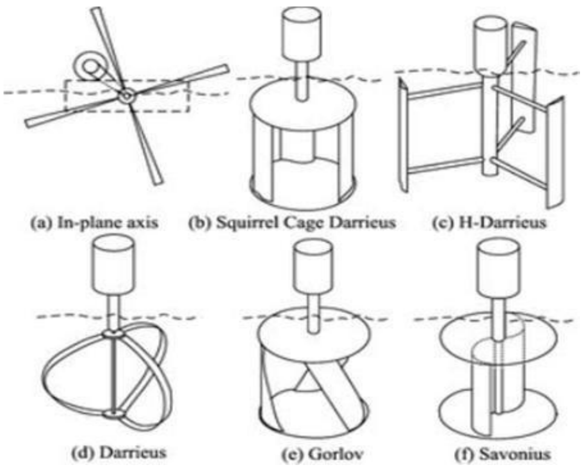

Figure 4 Vertical axis turbines [20]

River turbines operate under the influence of varying volumetric water flow through a river channel subject to various external factors such as, channel cross-section, rainfall, and artificial incidences (such as, transportation, upstream dam opening etc.).

Siting is more stringent in river channels as the usable space is limited and river transportation may further constrain the usability of the sites. There could also be varying types of suspended particles and materials (fish, debris, rock, etc.) in river channels depending on the geography of a site.

7. Siting Considerations

Several other characteristics of a water current site may pose conditions on an energy conversion system. In locating sites, the depth, available cross section, type of sea- or riverbed, other uses of the water, and proximity to land and an electric grid will be considered. Any equipment in the water will need to cope with turbulence, waves, ice, debris, plant-matter and animals.

Hydrokinetic (in-stream) turbines produce electricity from the free-flowing water in a river or stream – water in motion, or the velocity (speed in a specific direction) of the water. The best performance and the highest power production is obtained from a smooth, linear flow of water at high velocities.

Properly siting a hydrokinetic turbine requires an understanding of energy as it relates to water, and then what influences the kinetic energy (velocity) of the water at any given point in the river.

7.1 The Energy in Water

Kinetic systems, or instream systems, rely on the energy in the free-flowing water. This Movement results primarily from the gravitational forces acting on the surface of the water. Kinetic hydro systems require much more water volume.

Properly siting a hydrokinetic system requires an understanding of the dynamics of free-flowing water in the complex river environment. The magnitude of the system intended to be to installed will dictate the extent to which the site and the project are engineered.

7.2 The gradient of the river

As rivers travel to the sea, they follow the “lay of the land” (ground slope) which is constantly changing. This gradient, or slope to the river, corresponds to the ground over which it is travelling at that point. Some sections of river will have a steeper slope (often resulting in rapids) and others will have a very gentle slope (resulting in deep water pools). The steeper the slope or gradient, the greater the velocity or current speed. The gradient of the river is the most influential factor in current velocity. The optimal location for a hydrokinetic turbine is at the steepest gradient possible without incurring excessive turbulence.

7.3 The alignment of the river

There is less friction loss (and more velocity) in a Straight section of river than at a bend in the river. The most linear and stable water flow will normally be found in straight sections of river. If a bend in the river is the only option because of other considerations, the greatest velocity is in the outer portion of the bend. These areas can have problems, though, as the current will typically tend to undercut the outer bank and the effect of the water flow patterns at the bend can result in swirling cross flows that impact velocity.

7.4 The width and depth of the river

Friction is the major detriment to water velocity. Wider sections of river are generally shallower and have a higher percentage of ground contact (river bottom and banks) than narrower, deeper sections of river. This ground contact slows down the velocity – in fact the velocity at the point of contact is essentially zero – and the areas that are in closest proximity to the bottom and banks will have the lowest velocity. Areas next to the banks can develop rotating cross flows.

8. The Contour Of The River Bottom

8.1 The contour of the river bottom

If the contour of the river bottom (and hence the water depth) is uniform across the river, the greatest current speed is going to at the point that is the farthest from all ground contact – the upper centre of the river. If the contour is uneven, the greatest velocity will be in the upper centre of the portion that has the greatest depth.

8.2 Depth of the turbine rotor

The greatest velocity will normally be in the area below the surface from10% to 30% of the river depth at that point. If the river depth is 10 ft at that point, the greatest velocity will be between 1 ft and 3 ft below the surface. The areas of least velocity are next to the banks and at the river bottom. Ideally, the turbine rotor will fit within this 10%-30% high velocity area.

If the turbine must extend beyond this range, extend the turbine below the range, but take care to avoid the turbulent area next to the river bottom.

8.3 Cross-sectional Area

From the law of continuity sections of the river that have a smaller cross-sectional area will have a greater velocity. Because the same volume of water is passing through a smaller area at the same discharge rate as the larger cross-sectional areas, the water must move through that area faster.

8.4 Discharge volume

The velocity at a given point will be greater during periods of high water (due to rainfall, snow melt, etc.) than periods of low water levels. The reasons a combination of less friction –there is a higher volume of water flowing down the river relative to the ground surface contact – and increased force since there is a larger volume of water trying to move downstream.

8.5 The roughness of the river bottom

There are very few (if any) areas with truly linear water flow. The entire cross-section of the river can be considered turbulent. However, rough river bottoms (either rocky or uneven ground) increase friction and create excessive turbulence. Both friction and turbulence slow the water speed. Try to avoid siting the turbine in a shallow section of river where the turbine rotor will be exposed to excessive turbulence.

8.6 Obstacles

Obstacles or obstructions in the river create turbulence. Avoid these areas – particularly in the immediate downstream area.
Typical obstructions would be bridges or rocks.

8.7 Selecting the Site-the Water Resource

Ideally, pick a straight, narrow, and deep section of river with a relatively steep gradient that has no obstructions and a relatively smooth river bottom. Avoid excessive turbulence – the smoothness of the surface will give a good indication. Since installing the hydro turbine in the centre of the river can be difficult and a potential navigation hazard, select a section of river where the bottom contour is such that there is a deep section next to the bank. Position the turbine in the centre of that deeper spot but at least one river depth from the bank. If the river depth at that point is 2.5m, the turbine should be at least 2.5m from the bank.

9. Other Site Considerations

Other Site considerations may be:

9.1. Permits

Hydro installation may require local and/or state permits.

9.2. Turbine Mounting Structure

The turbine requires amounting structure which must be strong enough and secure enough to support the turbine during floods and other high water periods. The mounting structure must also allow for the turbine to be adjusted vertically as the water level in the river changes. If the turbine is to be mounted on a permanently affixed structure like a dock, the ability to adjust the turbine elevation and positioning of the turbine to avoid turbulence created by the dock are crucial. A floating boat or plat form is the easiest means of providing proper positioning of the turbine, but consideration must then be given to adequate anchoring of the floating structure.

9.3. Floating Debris

Some means must be provided to protect the turbine rotor from floating debris. A diversion rack on the upstream side of the turbine to deflect debris is common.

9.4. Fish

Typically, rivers that are suitable for these turbines will have fish populations. While these turbines have proven to have no appreciable impact on fish populations, this is an issue that should be given careful consideration. Site permits may require specific study or monitoring to ensure that there is no negative impact on fish populations.

9.5. Access to the Power Grid

To avoid excessive transmission line costs, the turbine should be sited reasonably close to the electrical load or electrical grid connection. Care should be taken to ensure that National Electrical Code requirements are complied with in the interconnect, particularly in the portion over the water.

9.6. Site Access

Ease of installation and maintenance dictates that the site should have reasonable access. If a pontoon boat or floating dock is used, siting the turbine close enough to shore for ramp access is beneficial.

9.7. Theft and Vandalism

These systems are a significant investment. It is prudent to take steps to ensure that they are protected. Equally important is to provide sufficient access protection so that children or curious individuals cannot inadvertently put themselves in harm's way.

9.8. River Navigation

These systems will often be in navigable waterways. When siting the turbine, it is important that the installation not conflict with transportation routes, creating a potential hazard. Often a permit requirement will be that the system be adequately lighted or otherwise marked to warn passers-by of its existence and location. This requirement also applies to anchoring and electrical transmission line.

10. Conclusions

The article above provides a fine overview of the current base of hydrokinetic energy for Hydrokinetic energy electricity generation, prospects of this technology as well as suitability of turbines for river currents and implementation challenges.

The author believes that the Hydrokinetic energy technology deploying vertical and horizontal axis have a bright future in both the stand alone and grid connected applications for distributed or centralized power production and are yet another tool to add to the mix of renewable energy options available where suitable water resources exist.

The opinion of the author is that South Africa and Botswana would greatly benefit when deploying this renewable energy technology.

Finally, it can be stated that hydrokinetic energy technologies are emerging as a viable solution for renewable power generation and significant research, development, and deployment initiatives need to be embarked upon before realizing true commercial success in this sector.

References

[1] Kari Sornes. “Small-scale water current turbines for river applications”. Zero Emission Resource Organization, January 2010.

[2] Available from: ⟨http://www. zero.no/publikasjoner/small-scalewater-current-turbines-for-river-applications.pdf⟩ [accessed 05.06.23].

[3] Güney M.S, Kaygusuz K. Hydrokinetic energy conversion systems: A technology Status Review. *Renewable and Sustainable Energy Reviews,* 2010; 14(9): 2996–3004.

[4] Paish O. Small hydropower: Technology and status. *Renewable and Sustainable Energy Reviews* 2002; 6(6): 537–56.

[5] University of Louisville (2009 August12). Sustainable power generation study. Project No.003142.00. Available from: ⟨http://louisville.edu/sustainability/operations/ Report%20%20Renewable%20Energy%20Op tions%20for%20UofL%20Cannon%20Design%208-1209.pdf/at download/file⟩[accessed 01.06.23].

[6] Williams G.G., Jain P. Renewable energy strategies. Sustain: A Journal of Environmental and Sustainability issues, The Kentucky Institute for the Environment and Sustainable Development, Issue23, 2011. p.29–42. Available from: ⟨http://louisville.edu/kiesd/sustain magazine/SUSTAIN-23.pdf⟩ [accessed 01.06.13].

[7] M.J. Khan, G. Bhuyan, M.T. Iqbal and J.E. Quaicoe; Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review, Applied Energy, October 2009, Pages 1823-1835 (ScienceDirect)

[8] R. H. Els, C. Campos, L. F. Balduino, A. M. Henriques, Hydrokinetic Turbine for Isolated Villages, in X Encontro Latino Americano e do Caribe em Pequenos Aproveitamentos Hidroenergéticos, Poços de Cldas, Minas Gerais, Department of Mechanical Engineering - University of Brasilia, May 2003, p-298-272. http://www.cerpch.unifei.edu.br/Adm/artigos/a10e4e0f6494ae3e6ab116b6d291d151.pdf

[9] A.K.M. Sadrul Islam, N.H. Al-Mamun, M.Q. Islam and D.G. Infield, Energy from river current for small scale electricity generation in Bangladesh, Proceedings of the renewable energy in maritime island climates, Solar Energy Society, UK, 2001.

[10] Al-Mamun N.H. Utilization of river current for small scale electricity generation in Bangladesh. Master's thesis, Department of Mechanical Engineering, BUET, Dhaka, July 2001

[11] Garman P. Water current turbines: Providing pumping, power in remote areas. Hydro Rev Worldwide 1998; 6(5): 24–8

[12] Vauthier P. The underwater electric kite east river deployment. In: Proceedings of A partnership of marine interests OCEANS '88, vol. 3; 1988. p. 1029–33.

[13] Previsic M, Polagye B. Deployment effects of marine renewable energy technologies—tidal energy scenarios, Report ID: REVision DE002, University of Washington, June2010. Available from: ⟨http://www.harveyecology.com/PDF/DOE/FINAL_TIDAL_SCENARIO_REPORT_MP_6-16-10.pdf⟩ [accessed 08.09.12].

[14] Gauntlett D. Resource assessment and feasibility study for use of hydrokinetic turbines in the tail waters of the Priest Rapids Project [M.Sc. Thesis]. University of Washington: Department of Mechanical Engineering; 2011.

[15] Lalander E. Modelling hydrokinetic energy resources for in-Stream Energy converters (thesis). Department of Engineering Sciences, Uppsala University; 2010. Available from: ⟨http://www.el.angstrom.uu.se/Seminar/Emili a_L/Emilia%20Lalander%20Lic%20Avhandling%202010-02-01.pdf⟩ [accessed 05.01.13].

[16] Briand M, Ng K. Kinetic energy recovery turbine technology: resource assessment and site development strategy. World Energy Conference, Issue 2.1: Energy resources and technologies, today and tomorrow,13–17 September 2010. Available from: ⟨http://www.worldenergy.org/documents/congress papers/441.pdf⟩ [accessed 10.06.13].

[17] Fraenkel, P.L and Musgrove, P. J., "Tidal and River Current Energy Systems"; Proc Inst. Conf. on Future Energy Concepts; Inst. of Electrical Engineers, London, January 1979.

[18] Duvoy P, Toniolo H. HYDROKAL: A module for in-stream hydrokinetic resource assessment. Computer & Geosciences 2012; 39: 171–81.

[19] Khan M.J, Bhuyan G, Iqbal M.T, Quaicoe J.E. Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review. Applied Energy 2009; 86(10): 1823–35.

[20] Khan MJ, Iqbal MT, Quaicoe JE. River current energy conversion systems: progress, prospects and challenges. Renewable and Sustainable Energy Reviews 2008; 12(8): 2177–93

[21] [20] Hydrovolts."In-stream Hydrokinetic Turbines". PowertechLabs, 2006. Available from: hydrovolts.com: ⟨http://hydrovolts.com/wpcontent/uploads/2011/06/In-StreamHydrokinetic-White-Paper2.pdf⟩ [accessed 06.06.23].

[22] Bahaj, A.S. and Myers, L.E. 2003, Fundamentals applicable to the utilization of marine current turbine for energy production, Renewable Energy 28, 2205-2211.

[23] Fernando Ponta and Gautam Shankar Dutt, An improved vertical-axis water-current turbine incorporating a channeling device, Renewable energy 20 (2000), 223-241.

[24] G Mac Pherson-Grant. 2005. (17) The Advantages of Ducted over Undusted Turbines 6th European Wave & Tidal Energy Conference Glasgow, September 2005.

[25] Previsic, M., Bedard, R. and Polagye, B. System level design, performance, cost and economic assessment – Alaska river in-stream power plants. EPRI Report EPRI-RP 006 Alaska, October 2008.

[26] Fraenkel, P. 2006. Tidal current energy technologies, Marine current turbine limited, the green, stoke Gifford, Bristol BS 34 8PD ,UK Ibis 148, 145-151.

[27] Ponta, F.L and Jacovki, P.M. 2008. Marine current power generation by diffuser- augmented floating hydro turbines, Renewable energy 33, 665-673.

[28] K. Thomas, “Low speed energy conversion from marine currents,” Ph.D. dissertation, Uppsala University, 2007.

[29] E. Segergren, “Direct drive generator for renewable power conversion from water currents,” Ph.D. dissertation, Uppsala University, 2006, ISBN 91-554-6362-2.

[30] M. Grabbe, “Marine current energy conversion – resource and technology,” Licentiate thesis, Uppsala University, 2009.

[31] E. Lalander, “Modelling the hydrokinetic energy resource for in-Stream Energy converters,” Licentiate thesis, Uppsala University, 2010.

[32] Al-Mamun N.H. Utilization of river current for small scale electricity generation in Bangladesh, master’s thesis, Department of Mechanical Engineering, BUET, Dhaka; July 2001.

[33] Sadrul Islam AKM, Al-Mamun NH, Islam MQ, Infield DG. Energy from river current for small scale electricity generation in Bangladesh. In: Proc. renewable energy in Maritime Island Climates. UK: Solar Energy Society; 2001.

[34] Garman P. Water current turbines: providing pumping, power in remote areas. Hydro Review Worldwide 1998; 6(5): 24–8.

[35] US Department of Energy, Energy Efficiency and Renewable Energy; Wind and Hydropower Technologies, Feasibility Assessment of the Water Energy Resources of the United States for New Low Power and Small Hydro Classes of Hydroelectric Plants, Tech. Rep. DOE-ID-11263; January 2006.

[36] Potential and Development Needs, Tech. Rep. 1014762, Electric Power Research Institute (EPRI); March 2007. <http://www.portdetroit.com/econdev/grantsm gmt/grantsmgmt_dte.htm>. Verdant Power Canada ULC., Technology Evaluation of Existing and Emerging Technologies – Water Current Turbines for River Applications, Tech. Rep. NRCan-0601071, Natural Resources Canada; June 2006.

Detroit River Hydrokinetic Energy Project; fieldworker’s guide. UK: Intermediate October 2008. Technology Publishing; 1986,

[37] David Gaden, Eric Bibeau, Increasing the power density of kinetic turbines for cost-effective distributed power generation. In: Power-gen, April 10–12, 2006, Mandalay Bay, Las Vegas, NV. Caddet Renewable Energy. Water current turbines pump drinking water. Available from: ⟨http://www.caddetre.org/assets/no83.pdf⟩ [accessed 11.09.12].

[38] Verdant Power, June 2006, Technology evaluation of existing and emerging technologies-water current turbines for river applications. Available from ⟨http://oreg.ca/web_documents/verdant_river_ turbines_report.pdf⟩ [accessed 11.10.23].

[39] J. Manwell, J. McGowan, and A. Rogers, Wind Energy Explained - Theory, Design and Application. West Sussex, England: John Wiley & Sons Ltd., 2002, Ch. 2.2.3.1, p. 31.

[40] G. A.T. Findlay, SI Chemical Data. Milton, Qld 4064: Jacaranda Wiley Ltd., 1994.

[41] Betz, A., Wind-Energie und ihre Ausnitzung durch Windmuehlen, Vanddehoeck & Ruprech, Goettingen, 1926 van Kuik, Gijs A.M., The Lanchester–Betz– Joukowsky Limit, Wind Energ. 2007; 10:289-291

[42] A.R. Turton, R. Meissner, P.M. Mampane, and O. Seremo, A Hydro-political history of South Africa’s International River Basins African Water Issues Research Unit (AWIRU), University of Pretoria, Report to the Water Research Commission WRC Report No. 1220/1/04, ISBN 1 77005 042 6, October 2004 0946688273.

[43] A.R. Turton, R. Meissner, P.M. Mampane, and O. Seremo, A Hydro-political history of South Africa’s

International River Basins African Water Issues Research Unit (AWIRU), University of Pretoria, Report to the Water Research Commission WRC Report No. 1220/1/04, ISBN 1 77005 042 6, October 2004

[44] Garman P. Water current turbines: a fieldworker's guide. UK: Intermediate Technology Publishing; 1986

[45] Al-Mamun N.H. Utilization of river current for small scale electricity generation in Bangladesh, Master's thesis, Department of Mechanical Engineering, BUET, Dhaka; July 2001.

[46] Sadrul Islam A.K.M, Al-Mamun N.H, Islam M.Q, Infield D.G. Energy from river current for small scale electricity generation in Bangladesh. In: Proc. Renewable energy in Maritime Island Climates. UK: Solar Energy Society; 2001.

[47] Marlec Engineering Co Ltd., Rutland House, Trevithick Rd, Corby Northants, NN17 5XY; October 2008.

[48] Thropton Energy Services, Physic Lane, Thropton, Northumberland NE65 7HU, United Kingdom. October 2008.

[49] CADDET Centre for Renewable Energy, ETSU, Harwell, Oxfordshire OX11 0RA, UK; October 2008.

[50] Marine Current Turbines Ltd., The Court, The Green Stoke Gifford, Bristol, BS34 8PD, UK; October 2008.

[51] Hammerfest STRM AS, Norway; October 2008.

[52] Tuckey A.M, Patterson D.J, Swenson J. A kinetic energy tidal generator in the Northern Territory-results. In: Proc. IECON, vol. 2. IEEE; 1997. p. 937–42.

[53] M.J. Khan, G. Bhuyan, M.T. Iqbal and J.E. Quaicoe; Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review, Applied Energy, October 2009, Pages 1823- 1835 (Science Direct)