SCIREA Journal of Energy

http://www.scirea.org/journal/Energy

January 8, 2018

Volume 3, Issue 1, February 2018

Hydrokinetic Energy Production from Downstream Currents in the Exit of Hydropower Plant: A Review

T. Nzualo[1,*], R.Y.Qassim[1], P.C.C, Rosman[1,2]

[1]Department of Ocean Engineering, The Federal University of Rio de Janeiro, Ilha do Fundão, Rio de Janeiro, RJ, 21945-972, Brazil,

[2]Department of Water Resources, The Federal University of Rio de Janeiro, Ilha do Fundão, Rio de Janeiro, RJ, 21945-972, Brazil

E-mail: raadqassim{AT}hotmail.com

Abstract

The quest for new renewable energy resources is intensifying, with a view to greenhouse gas emission reduction and in the context of the climate-food-water-energy nexus. A hitherto ignored though widely available renewable energy resource lies in downstream water flow exiting from existent hydroelectric power plant. The techno-economic feasibility of this renewable energy resource is enhanced by two factors: mature hydrokinetic river turbine technology and availability of data on the river channel flow downstream of hydro power plant. The main challenge lies in determination of the optimal hydrokinetic turbine placement downstream of hydro power plant. This challenge has stimulated research work both on the tidal and the river current variants of the turbine, turbine fence, and turbine farm layout problems. The renewable energy resource under consideration in this paper is of particular importance to countries with substantial hydro power generation, the leaders in the world at the present time being in descending order: China, Brazil, and Canada.

Keywords: Hydroelectric Power; Hydrokinetic Energy; Downstream Channel; Renewable Energy; Turbine Placement; Optimisation

1. Introduction

The increasing role of renewable energy in the generation of energy supply to ensure the energy demand for economic growth is unquestionable, and has been enhanced by the incessant international effort towards sustainable development encompassing the nexus of food, energy, water, and climate [1,2]. Amongst all other renewable energies, one is in a paradoxical position: hydrokinetic energy in downstream fluid flow of existent hydroelectric power plant. The paradox alluded to arises in view of the fact that this resource *exists* and all that is needed for it to be recovered by appropriate extraction device technology, which also exists and advancing at great pace is *implementation studies* in specific cases; yet, this resource has only begun to be studied in the last few years. This paper presents the present status and future prospects of this renewable energy resource.

Worldwide, the installed capacity of hydropower plants exceeds 1000 GW [3]. Leading countries are China (279 GW), Brazil (89 GW), United States (79 GW), Canada (77 GW) and Russia (49 GW). In terms of electricity production, globally hydropower supplies 16% of the total electricity generation and is the most important source of renewable power, with 85%. In Fig.1, the amount of hydropower by country are shown [4]. It is clear that the potential for the development of hydrokinetic energy downstream of power plants would be most promising in the aforesaid countries.

Hydrokinetic energy is a renewable energy resource for the production of electrical power by harnessing the kinetic energy of a body of water; i.e., the energy that results from the motion of the water body. There are two major types of this energy resource, which have been shown to be highly promising for the commercial generation of electrical power: tidal currents and river currents.

Tidal current energy conversion to electrical power has been studied for more than two decades, with a focus on the identification of specific promising geographical sites in various parts of the world, such as Canada [3], the UK [4], China [5], Brazil [6], and Norway [7], amongst others. The reported research work covers two major aspects: assessment of the tidal resource at specific promising geographical sites, employing computational fluid dynamics (CFD) models which have been calibrated by appropriate measurements of site tidal current circulation, water level, and bathymetry.

The second type of hydrokinetic energy production is that employing river currents. Analogously to tidal current energy conversion to electricity, the production of electrical power from river currents has been extensively studied in the last couple of decades. Technical reviews and resource assessment techniques, may be found in [8-13].

River current energy extraction devices (turbines) function in accordance with the same principles as tidal current turbines, and also possess similar geometric configurations. The major difference lies in the significantly smaller size of river current turbines in comparison with tidal current turbines, in view of the shallower depths involved and the lower power produced in river current energy applications; for reviews of hydrokinetic turbine technology, see [14-18].

More recently, interest has been shown in the promising potential inherent in outflow water streams exiting from hydroelectric power plant, in view of the fact that such streams possess high velocities, which make them attractive for hydrokinetic conversion energy to electrical power. It is the objective of this paper to provide a review of this aspect of hydrokinetic energy conversion to electrical power production, which is of particular interest to countries where hydropower plays a major part in national energy generation.

2. Literature review

The existence of an extensive literature on hydrokinetic river current energy withstanding, there has been surprisingly little work reported on the recovery of kinetic energy from fluid flow downstream of hydroelectric power plant. Lalander and Leijon [19] present a case study in Sweden, whose focus is on the effect of the presence of hydrokinetic turbines in the downstream flow on the water level in hydroelectri power plant upstream. For that purpose, an analytical/numerical computational fluid dynamics

(CFD) model has been implemented in the MIKE code, and calibrated using fluid velocity and fluid level measurements, employing the Acoustic Doppler Current Profiler (ADCP) technique. The major conclusion of [19] is two - fold:

- the placement of a hydrokinetic energy device downstream of hydroelectric power plant leads to a head loss at the upstream power plant, due to the energy harvested, internal losses in the fluid flow field, and device wake mixing, and consequently, for the *specific case* under consideration, hydrokinetic energy extraction devices has not been considered recommendable;
- the MIKE code has not accounted adequately for the head loss connected with the hydrokinetic extraction devices.

Liu and Packey [20] draw attention to the potential of kinetic energy in hydroelectric power plant downstream flow, and propose that there are two modes of extraction of this energy:

- Placement of the hydrokinetic turbine directly behind the turbine of the hydro electric power plant;
- Placement of the turbine in the vicinity of the hydro power plant powerhouse

Shafei et al. [21] point out that downstream of the gates hydroelectric power plant, there is substantial kinetic energy in the water jet, and propose that a hydrokinetic turbine farm be placed on the stilling basin of the spillways of the hydro power plant. A laboratory experimental facility is used to simulate the actual hydroelectric power plant system.

Arango [22] present a feasibility study of the installation of hydrokinetic turbines downstream of hydroelectric power plant. CFD simulation is employed to determine the fluid velocity profiles for several potential sites where hydrokinetic turbines may be placed for the purpose of energy extraction.

3. Hydrokinetic energy extraction downstream of hydro power plant

It is quite clear that from Sections 1 and 2 of this paper that the extraction of kinetic energy from fluid flow downstream of conventional hydroelectric power plant constitutes a highly promising potential source of renewable energy, which is particularly attractive for countries with a significant existent hydroelectric power generation supply to meet their respective energy demand for sustainable growth. In order to transform this potential promise into reality, a number of technical questions need to be answered. It is the purpose of this Section to define these questions and indicate the roads to provide the answers to them.

3.1. What is the theoretically available amount of energy ?

Given a hydroelectric power plant, whether in the design phase or in actual operation, the first question that arises naturally in the context of downstream fluid kinetic energy extraction is this: what is the theoretically *available amount of kinetic energy that is extractable* from the downstream flow ? The determination of this amount of energy is a necessary prerequisite to considering the subsequent questions with regard to the determination of the fraction of this energy that may be extracted by the placement of hydrokinetic turbines.

The theoretically available power (energy per unit time) P_{th} is given by [9]

$$P_{th} = \gamma Q \Delta H \ , \ (1)$$

where

P_{th} depicts the specific weight of water, Q depicts the volumetric flow rate, and ΔH depicts the change in hydraulic head between the entry and the exit of the flow section under consideration; i.e., the flow section downstream of the hydroelectric power plant. From Eq. (1), it is clear that the determination of the theoretically available power, and therefore energy, depends on the downstream flow configuration of the hydroelectric power plant, starting from the turbines of the hydroelectric power plant itself and extending to the river stretch downstream. As every *specific* hydro power station possesses a *specific* downstream flow configuration, which depends on the design of the hydro power plant and and its environmental licencing requirements, the determination of the theoretically available energy is *plant specific*. In view of the typically complex geometry of the downstream flow configuration of a hydroelectric power plant and the complex turbulent flow therein, the calculation of the theoretically available energy needs to be carried out through the development of a CFD model, using appropriate CFD software. Such a model needs to be calibrated by data collected in situ comprising water volumetric flow rate, downstream channel length and slope.

3.2. What is the technically recoverable amount of energy ?

The *amount of technically recoverable amount of energy* depends on the hydrokinetic turbine technology employed, and its value is a fraction of the theoretically available amount of energy due to feedback effects of energy extraction on flow depth and velocity, in addition to turbine wake losses. This is because the presence of an extraction device (hydrokinetic turbine) alters the flow that holds in its absence. The influence of hydrokinetic turbines on the fluid flow field is discussed in the next Subsection.

3.3. Hydrokinetic energy extraction device design and placement

Once the hydrokinetic resource is quantified and found promising, the next question that arises naturally is this: *how to extract the available hydrokinetic energy in the most economical manner* ? First and foremost, it is a fact that hydrokinetic energy extraction devices are turbines which are based on one of several concepts, as indeed is the case with tidal current turbines. It has been established that at the present state of turbine technology, for both tidal current and river current energy applications, the horizontal axis turbine concept, with its axis parallel to the principal direction of fluid flow, is the most efficient and consequently more widely employed type. Indeed for the horizontal axis turbine, commercial off-the-shelf designs are available for various channel widths and depths and fluid velocity ranges, though in specific cases a turbine design may be customised for techno-economic reasons. In other words, the *turbine design problem* is in fact a *turbine selection problem* for the specific hydrokinetic energy extraction case under consideration.

The second and considerably more difficult problem than the turbine design problem described in the last paragraph is the *hydrokinetic turbine placement problem* (HTBP). In the HTBP, the following questions are addressed:

- if a single turbine or single turbine fence is installed, at which longitudinal position in the river channel is it to be installed ?
- if a multiple turbine or multiple fence is installed, at which longitudinal positions in the river channel are they to be installed and how many turbines or turbine fences are to be installed ?

• if a turbine farm is installed, what are the spatial positions of the turbines constituting the farm ?

It may be worth noting that in essence, the HTPB is a variant, albeit a very complex one, of the classical facility location problem (FLP) of operations research [23]. The complexity of the HTPB arises from the feature, which is naturally absent in the FLP (flow is irrelevant in the FLP), that the HTPB requires for its solution the simultaneous solution of two sub-problems: determination of the fluid flow field *and* the determination of the longitudinal position (s) of the turbine (s) or turbine fence (s) or the determination of the layout of the turbine farm ?

In the tidal variant of the HTPB, the two sub-problems have been formulated and solved in a hybrid sequential-simultaneous fashion, whereby an assumed set of turbine locations is assumed first and subsequently the fluid flow field is determined employing CFD modelling [24-25]. Needless to say such a hybrid procedure is likely to furnish a sub-optimal solution to a problem, which consists of two sub-problems, that needs to be attacked head-on in order to ensure an optimal solution. This has not yet been done in the tidal variant of the HTPB. As the river variant of HTPB is simpler than its tidal counterpart, in view of the highly more complex geometry of tidal current turbine farms than that of river turbine current fences and farms, a direct attack on the river variant of the HTPB is possible. This is a subject of ongoing research on the part of the authors of this paper.

4. Conclusions

Given the existent installed hydroelectric power capacity in the world, there is an enormous potential for the recovery of the renewable resource in hydroelectric power plant downstream fluid flow. Hydrokinetic turbine technology for the extraction of this energy resource is available both off the shelf and customised. As river channels downstream of hydro power plants are regulated, as part of the licensing of hydroelectric power plant, reliable data on the downstream river channel is normally available, thus facilitating the assessment of the hydrokinetic energy resource. These factors, available hydrokinetic turbine technology and mapped site, enhance the feasibility of the exploration of this renewable energy resource. The immediate need is for advances in the solution methods of the optimal turbine placement problem in river channels downstream of hydro power plant, with a view to extracting the maximum amount of energy at least cost.

References

[1] Endo A, Tsurita, I, Burnett, K., Orencio, PM. A review of the current state of research on the water, energy, and food nexus. Journal of Hydrology: Regional Studies 2015 doi: 10.1016/j.ejrh.2025.11.010.

[2] Borthwick AGL. Marine renewable energy seascape. Engineering 2016:2:69-78.

[3] International Hydropower Association, 2014, www.hydropower.org (accessed 19-05-2016).

[4] Energy Information Administration, 2012, www.eia.gov, (accessed 19.05.2016).

[5] Karsten R, Swan A, Culina, J. Assessment of arrays of in-stream tidal turbines in the Bay of Fundy. Philosophical Transactions of the Royal Society 2015 doi: 10.1098/rsta.2012.0189.

[6] Iyer AS, Couch SJ, Harrison, GP, Wallace, AR. (2013) Variability and phasing of tidal current energy around the United Kingdom. Renewable Energy 2013; 343-357.

[7] Zhang Y-l, Lin Z, Liu Q-l. Marine renewable energy in china: Current status and perspectives. Water Science and Engineering 2014; 7(3) 288-305.

[8] González-Gorbeña E, Rosman PCCR, Qassim RY. Assessment of the tidal current energy resource in São Marcos Bay, Brazil. Journal of Ocean Engineering and Marine Energy 2015; 1, 421-433.

[9] Carpman N, Thomas K. Tidal resource characterization in the Folda Fjord, Norway. International Journal of Marine Energy 2016; 13, 27-44.

[10] Ortega-Achury SL, McAnally WH, Davis TE, Martin JL. Hydrokinetic Power Review. Mississipi State University 2010.

[11] Electric Power Research Institute. Assessment and mapping of the riverine hydrokinetic resource in the continental United States 2012.

[12] VanZwieten J, McAnlly W, Ahmad J, Davis T, Martin J, Bevenlhimer M, Cribbs A, Lippert R, Hudon T, Trudeau M. In-stream hydrokinetic power: Review and appraisal. ASCE Journal of Energy Engineering 2015; 141(3).

[13] Petrie J, Diplas P, Gutireerz M, Nam S. Characterizing the mean flow field in rivers for resource and environmental impact assessments of hydrokinetic energy generation. Renewable Energy 2014; 393-401.

[14] Kalnach A, Kalnach J, Mutule, A, Persia U. Potential of the Lower Daugava for siting hydrokinetic turbines. Latvian Journal of Physics and Technical Sciences 2013(2), doi: 10.2478Ipts-2013-0007.

[15] Kalnacs A, Kalnacs J, Mutule A, Persis U. Methods for estimation of the riverflow potential for hydrokinetic power generation. Latvian Journal of Physics and Technical sciences 2014(2), doi: 10.2478/Ipts-2014-0008.

[16] Khan MJ, Bhuyan G, Iqbal MT, Quaice JE. Hydrokinetic energy conversion systems and assessment of horizontal and vertical axis turbines for river and tidal applications: A technology status review.

[17] Søres K. Small-scale water current turbines for river applications. Zero Emission Organisation Report, 2010. www.zero.no, (accessed 14.05.2016).

[18] Güney MS, Kaygusuz K. Hydrokinetic energy conversion systems: A technology status review. Renewable and Sustainable Energy Reviews 2010;14:2996-3004.

[19] Vermaak HJ, Kusakana K, Koko SP. Status of micro-hydrokinetic river technology in rural applications: A review of the literature. Renewable and Sustainable Energy Reviews 2014; 29:625-633.

[20] Kumar D, Sarkar S, A review on the technology , performance, design optimization, reliability, techno-economics and environmental impacts of hydrokinetic conversion systems. Renewable and Sustainable Energy Reviews 2016; 58:796-813.

[21] Lalander E, Leijon M. In-stream energy converters in a river – Effects on upstream hydropower station. Renewable Energy 2011;36;399-404.

[22] Liu Y, Packey DJ. Combined-cycle hydropower systems – The potential of applying hydrokinetic turbines in the tailwaters of existing conventional hydropower stations. Renewable Energy 2014; 66:414-426.

[23] Shafei, ARS, Ibrahim DK, Ali AM, Younes MAA, El-Zahab E-DA. Novel approach for hydrokinetic turbine applications. Energy for Sustainable Development 2014; 66:414-426.

[24] Arango MA. Resource assessment and feasibility study for use of hydrokinetic turbines of the Priest Rapids Project. M.Sc. thesis, University of Washington, 2011.

[25] Farahani RZ, Hekmatfar M, Fahimnia B, Kazemzadeh N. Hierarchical facility location problems: Models, classifications, techniques, and applications. Computers and Industrial Engineering 2014; 68:104-117.

[26] Calley DM, Fuke SSW, Kramer SC, Piggott MD. Renewable Energy 2016; 85:215-227.

[27] González-Gorbeña E, Qassim RY, Rosman, PCC. Optimisation of hydrokinetic turbine layouts via surrogate modelling. Renewable Energy 2016; 93:45-57.