DYNA
ISSN: 0012-7353
ISSN: 2346-2183
Universidad Nacional de Colombia

Aristizábal-Tique, Víctor H.; Villegas-Quiceno, Adriana P.; Arbeláez-Pérez, Oscar F.; Colmenares-Quintero, Ramón F.; Vélez-Hoyos, Francisco J.

Development of riverine hydrokinetic energy systems in Colombia and other world regions: a review of case studies

DYNA, vol. 88, no. 217, 2021, April-June, pp. 256-264
Universidad Nacional de Colombia

DOI: https://doi.org/10.15446/dyna.v88n217.93098

DYNA
http://dyna.medellin.unal.edu.co/

UNIVERSIDAD NACIONAL DE COLOMBIA

Development of riverine hydrokinetic energy systems in Colombia and other world regions: a review of case studies

Víctor H. Aristizábal-Tique, Adriana P. Villegas-Quiceno, Oscar F. Arbeláez-Pérez, Ramón F. Colmenares-Quintero & Francisco J. Vélez-Hoyos

Facultad de Ingeniería, Universidad Cooperativa de Colombia, Medellín, Colombia. vharisti@yahoo.com, adriana.villegas@ucc.edu.co, oscar.arbelaez@campusucc.edu.co, ramon.colmenaresq@ucc.edu.co, francisco.velezh@campusucc.edu.co

Received: January 26th, 2021. Received in revised form: April 20th, 2021. Accepted: April 30th, 2021.

Abstract
At a global level, hydrokinetic power has been considered as a renewable energy source, and it has become an attractive alternative for the rural electrification of non-interconnected areas with the presence of water resources. Aspects such as the low rural electrification rate, the increase in energy demand, the decrease in fossil reserves and the climate change, are some of the factors that have driven the use of this technology for the electricity production. The aim of this work is to give a review of the hydrokinetic energy potential of water resources, the requirements and impacts of the implementation of hydrokinetic technology in different countries, and the current development in the Colombian case. At present, it can be observed that the implementation of this technology in different regions of the world, especially in Colombia, has several challenges and barriers, including gaps in knowledge, information and data, such as well as limitations of water resources and infrastructure, finally, impacting on a low adoption of this technology. On the other hand, publications on studies of implementation and potential of hydrokinetic technology have been increasing over time, indicating that this topic has been gaining interest despite the challenges.

Keywords: hydrokinetic power; hydrokinetic energy; hydrokinetic turbines; hydrokinetic river technology; river energy; river turbine; case study.

Desarrollo de sistemas de energía hidrocinética fluvial en Colombia y otras regiones del mundo: una revisión de estudios de caso

Resumen
A nivel mundial, la energía hidrocinética ha sido considerada como una fuente de energía renovable, y se ha convertido en una alternativa atractiva para la electrificación rural de zonas no interconectadas con presencia de recursos hídricos. Aspectos como la baja tasa de electrificación rural, el aumento de la demanda energética, la disminución de las reservas fósiles y el cambio climático, son algunos de los factores que han impulsado el uso de esta tecnología para la producción de electricidad. El objetivo de este trabajo es hacer una revisión del potencial energético hidrocinético de los recursos hídricos, los requerimientos e impactos de la implementación de la tecnología hidrocinética en diferentes países, y el desarrollo actual en el caso colombiano. En la actualidad, se puede observar que la implementación de esta tecnología en diferentes regiones del mundo, especialmente en Colombia, presenta varios retos y barreras, entre los que se encuentran los vacíos de conocimiento, información y datos, así como las limitaciones del recurso hídrico y de la infraestructura, repercutiendo finalmente en una baja adopción de esta tecnología. Por otro lado, las publicaciones sobre estudios de implementación y potencial de la tecnología hidrocinética han ido aumentando con el tiempo, lo que indica que este tema ha ido ganando interés a pesar de los desafíos.

Palabras clave: potencia hidrocinética; energía hidrocinética; turbinas hidrocinéticas; tecnología fluvial hidrocinética; energía fluvial; turbina de río; caso de estudio.

1. Introduction

The increasing energy demand and the ongoing transition from fossil fuel hegemony to multi-energy supply [1], the non-access to an electric power grid of some regions and the harmful environmental effects have motivated the search for new alternative energy sources [2]. In this regard, the renewable energies emerge as sources of clean and

How to cite: Aristizábal-Tique, V.H., Villegas-Quiceno, A,P., Arbeláez-Pérez, O.F., Colmenares-Quintero, R.F. and Vélez-Hoyos, F.J., Development of riverine hydrokinetic energy systems in Colombia and other world regions: a review of case studies.. DYNA, 88(217), pp. 256-264, April - June, 2021.

regenerative energy that could improve the energetic security and reduce the greenhouse gases emission [3,4], as is the hydropower energy. Moreover, in rural communities with a widely access to the rivers, hydropower energy has been considered the best energy source option for producing electricity [4].

Two approaches to obtain electric energy from the water can be differentiated: the hydrostatic energy and the hydrokinetic energy. In the hydrostatic energy, the water is stored in reservoirs in order to create a pressure head and to obtain the potential energy of water. On the other hand, the hydrokinetic energy is obtained by using of the streams of rivers with suitable speed values [4].

In general, the hydrostatic sources have environmental problems and high social impacts, therefore, this type of energy is considered as non-renewable source by some researchers and organizations. On the other hand, hydrokinetic energy is still considered as a renewable energy source, since this type of plants does not cause problems such as resettlement of populations, deforestation and its environmental impact is low [4,5]. Although this technology has some technical disadvantages, such as the relatively small production, the high sensitivity of the energetic supply to variations of the seasons, the cavitation problems in turbines and the block of navigation and fishing in rivers that can be generated by the installation of turbines, the following advantages promote the research and implementation of this technology [4,6]:

a. The hydrokinetic energy presents greater possibility of extracting power than wind energy, even a low speeds of river in comparison with low speeds of the wind, given that the water is 800 times denser than the wind [4,6].
b. The provision of electrification in regions close to rivers, where the construction of dams is unviable due to the irregularities on the topography and geology, is possible with the hydrokinetic energy [4,6].
c. The natural conformation of region is not seriously affected by the presence of hydrokinetic systems [4,6].

These advantages have increased the use of hydrokinetic energy in order to attend the energetic demands in rural sites where there is no access to electric power grid and that present a high dependency on fossil fuels as diesel, gasoline and LPG (Liquefied Petroleum Gas) among others [6]. In this work, a review about applications, challenges and achievements of the application of hydrokinetic energy in different countries and the potential applications and advances for the Colombian Case is presented.

This paper is divided in four sections. The second section introduces the main technological and social aspects for this technology, in the third one, presents an overview about studies, applications and advances of the hydropower energy in the world context. Finally, the section four presents the general conclusions.

2. Technological and social aspects of the hydrokinetic energy

The available hydrokinetic power is function of the speed, the depth and the flow of the river. In following, some features for the operation of hydrokinetic turbines are presented:

a. The minimum current required to operate is around 0.5-2 m/s, based on the type of device selected. The optimum currents are found in a range of 1.5-3.5 m/s [6].
b. The water depth is an important factor in the total energy that can be extracted from a site, since the cross-section area over which a turbine can extract energy is dependent on suitable water level above the installed device [7].
c. The ideal installation locations for hydrokinetic devices are in sites where the rivers has more or less steady flow throughout the year and that are not prone to serious flood events, turbulence, or extended periods of low water level or droughts [7].

In several publications, the technical features and performance of the hydrokinetic turbines are described [6,8–15]. In this work, the 2 most common arrangement of small-scale hydrokinetic turbines are treated, where they are classified according to the turbine types and axis alignment of rotor with respect to the water flow (see Table 1 and Fig. 1):

I. Axial flow turbine: this configuration is also called horizontal axis, here the turbine has a rotor axis parallel to the incoming water stream.
II. Cross flow turbine: this configuration can be divided in vertical axis and in-plan axis, where the rotor axis is vertical and parallel to the water surface, respectively, but orthogonal to the incoming water stream.

Table 1.
Comparison between cross and axial flow hydrokinetic turbines [6,11,13,16,17]

Feature	Cross flow	Axial flow
Manufacturing cost	Low	Higher
Transportation cost	Low	Higher
Maintenance cost	Low	Higher
Rotor shape	Cylindrical shape	Disc shape
Airfoil shape	Does not need	Yes
Blade size	Configured with smaller and simpler blade	Large
Self-starting capability	No	Yes
Problems in river stream	Can deflect incoming debris	Clogged with debris found in rivers
Installation ability	Deploy as a single unit in small rivers and stacked together to deploy in bigger rivers	Only as single unit due to disc-shaped rotor and impossible to deploy in small, narrow river
Other requirements	No requirements	Requirements for water sealed components, as generator, gearing, and bearing among others.
Generator coupling costs	Low	Higher
Minimum speed (m/s)	>0.5	>0.7
Efficiency	Low	Higher
The most suitable applications	To extract the energy from river, irrigation canal, industrial flow and shallow channels.	To extract the energy from the tidal, marine current and deep channels.

Source: Elaborated by the authors

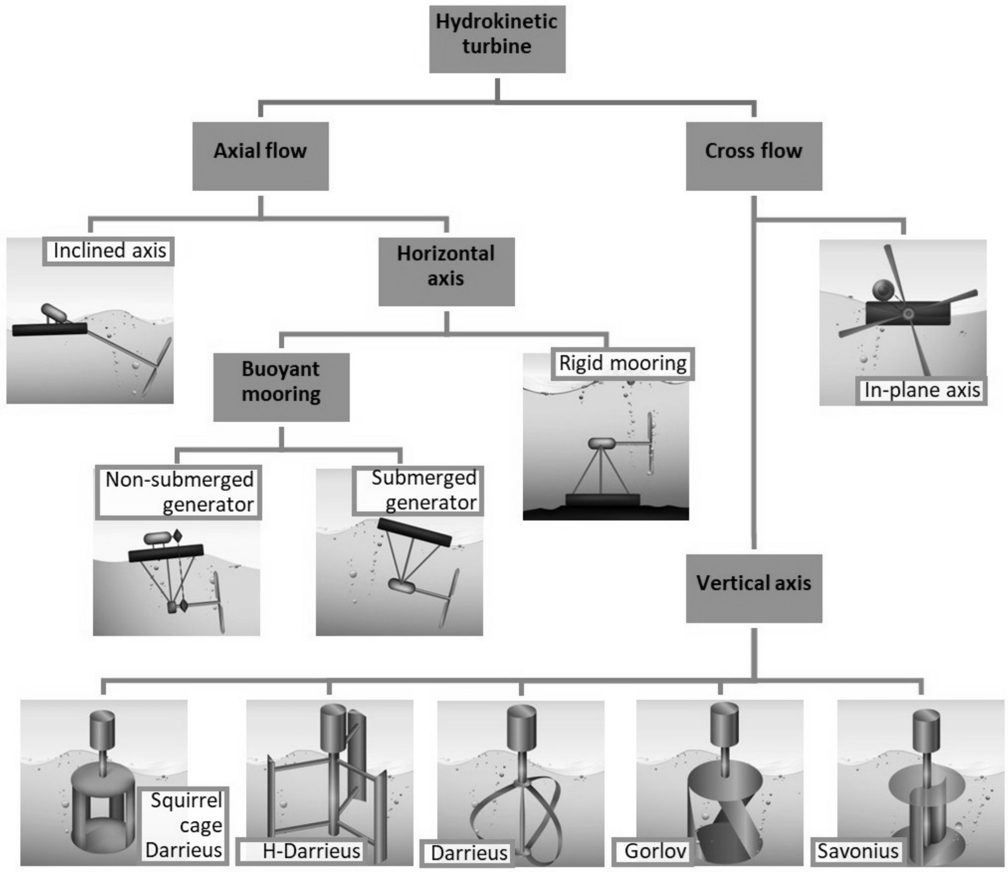

Figure 1. Classification of Hydrokinetic turbines.
Source: adapted from [12].

The impact of turbine operation on the aquatic environment is one of the most important aspects that will determine the development and the intervention of the different agencies whether private or governmental toward implementation of this new technology. In this order of ideas, this technology has several challenges that must be overcome such as the effect caused in the turbine operation by debris, sediments and the instability of the rivers in terms of turbulence, current, and velocity and the effect of the turbine operation on fish and marine mammals and their habitat [7].In social terms, small scale hydropower is one of the most economical and environmentally friendly technologies to be considered for rural electrification projects, since this technology does not have the high cost associated to the installation of the grid extension and it avoids the need of the use of fossil fuels. On the other hand, Hydrokinetic energy can be complemented to a solar energy, and it produces electricity for 24h a day as long as the running water is available and it is a much more concentrated energy resource than either wind or solar power [6]. However, the challenges that inhibin the development of this technology are associated to the lack of research demonstrating the technical, economic, and environmental benefits. It is necessary to implement about techno-economic analysis that include the cost of capital, maintenance and operation [6].

3. Overview about studies, applications and advances of the hydrokinetic energy in the world

The evaluated articles are presented in Table 2, listed in alphabetical order by country name and in chronological order for each country, along with a short summary of the study and results. The reviewed case studies can be categorized into 3 groups:

I. Studies where the assessment of the theoretical hydrokinetic power and the potential use of hydrokinetic turbines in a particular river is carried out. These types of studies are usually done through analytical or numerical simulations that are based on key hydrological, hydraulic, geometric parameters and technical data of the equipment, which are obtained from historical data, field visits and manufacturer's data sheet.

II. Studies with experimental tests and performance evaluation that were conducted at a particular point of a specific river, obtaining in this way, the efficiency and the main problems that arise during the installation and operation of a hydrokinetic turbine.

III. Research works that, considering the rivers characteristics of the specific region, gives rise to the design, numerical modeling, optimization and construction of hydrokinetic turbines prototypes using human talent, technology and local physical resources.

Table 2.
Articles analyzed according to authors, year of publication, study and main results.

Authors, year of publication and country	Study	Results
[18] Kirke (2011) Australia & Canada	Performance tests were conducted in Australia (Nerang River in Queensland) and Canada (Campbell River) on Hydrokinetic turbines with fixed and variable pitch straight blades, fixed helical blades, with and without a slatted diffuser, motoring through still water at speeds ranging from less than 1 m/s up to 5 m/s.	The turbine with fixed pitch, straight blades was found to shake violently due to cyclical hydrodynamic forces on blades, while the helical and variable pitch turbines did not shake excessively. Ducts can increase power output up to 3-fold but increase cost and complexity.
[19] Van Els and Brasil Junior (2015), Brazil	In this work, a brief account about several studies and pilot projects executed to use the hydrokinetic energy in water flows to generate electricity for remote communities, in Brazil, without access to electric power grid is made. The most notorious cases are: In 1985, Harwood tested several concepts on hydrokinetic turbines in the large Amazonian rivers and was a precursor on the use of floaters and inclined axes to fix the turbines. In 1991, the University of Brasilia developed an axial turbine and was installed in a region with a very constant river flow with little difference in water level in the dry and rainy season. In the 2000s, several hydrokinetic turbines were developed and installed in the Brazilian hinterland.	Most of the turbines were developed and build handcrafted and reached capacities from 300W until 2000W. The presented main problems were detritus, anchoring and other typical problems of the Amazon, such as seasonality and large differences between the dry and rainy season. On the other hand, most of the innovations achieved were result of empirical research to overcome the challenge to deal with anchoring systems, ducting, debris protection and simplified maintenance.
[20] Holanda et al. (2017) Brazil	A simulation case study for using remaining energy downstream the Tucuruí hydroelectric power plant in Brazil, via the installation of hydrokinetic turbines.	Analyses shows that a 10 turbines configuration can generate 2.04 GWh/year of electricity.
[21] Montoya et al. (2016) Colombia	Assessment of the potential use of hydrokinetic turbines in the discharge channels of two large hydro power plants in Colombia, through of the analysis of the hydraulic characteristics and discharge flows of the channels. These plants have capacity of around 1000 MW, where the first is operated by a Francis turbine and the other by a Pelton turbine.	The technology is not feasible for the conditions of the Colombian market in 2016, but it is recommended to monitor the situation to identify the right moment for its optimal use in the future.
[22] Ulvmyr (2016) Colombia	A field study was conducted to characterize the Amazon River and obtain experimental data such as the speed and amount of sediment. This collected data is analyzed and used to feed numerical simulations of a hydrokinetic turbine model.	The simulation, for the case of the Amazon River, shows that the turbine can be exposed to 12000 higher erosive wear than in the cases of European rivers, this is mainly due to the greater amount of sediment and the high speed of the water. This study indicates the need to reinforce the turbine with a grid to prolong its lifetime, but this in turn can decrease the power output by up to 46%.
[23] Ramirez-Tovar et al. (2017) Colombia	A micro H-Darrieus water turbine prototype was designed, modeled numerically, optimized and built using 3D-printing process in a digital fabrication lab in Cali, Valle del Cauca.	The simulation shows that the micro turbine system for rural applications can produce 380 W of peak power. A first prototype, at 1:10 scale, is made using a 3D printing technique with ABS polymer; and a second full-scale blade prototype, is made in balsa wood with by laser cutting of NACA. No experimental validation. The work contributes to the local appropriation of knowledge on this subject.
[24] Chica-Arrieta et al. (2018) Colombia	A scale-model three twisted blades hydrokinetic turbine was designed, modeled numerically, optimized and built in a local CNC machining center. This prototype was tested experimentally with different water velocities in a recirculating water channel. These studies were carried out in the labs of the Universidad de Antioquia and Instituto Tecnológico Metropolitano in Medellín.	Good agreement between simulated and experimental results was presented. The work contributes, on the one hand, to the characterization and understanding of the physical phenomenon involved in the hydrodynamic behavior of the hydrokinetic turbine; and on the other, to the local appropriation of knowledge on this subject.
[25] Chica et al. (2018) Colombia	Design, manufacture and experimental evaluation of a hydrokinetic turbine of 1 kW, type hydrofoil profile S822 , in Sinú River, Cordoba.	It was observed that the turbine starts automatically at speeds close to 0.625 m / s. The average efficiency of the system was around 0.5359. From a manufacturing point of view, the turbine could be manufactured using a wide range of methods, ranging from hand-carving to CNC machines, generating favorable scenarios for the local appropriation of knowledge on the subject.
[26] Ramirez-Tovar et al. (2018) Colombia	In Rozo, Valle del Cauca, a performance study of a system that use a Garman turbine has been made.	The system achieved a peak power of 0.4 kW with 2 m/s river speed.
[27] Fabregas et al. (2018) Colombia	Design and simulation of a fully submerged three-bladed horizontal axis hydrokinetic turbine for electricity generation, where the model is fed with experimental data obtained from measurements and field visits to the Magdalena River, which has a large flow near its mouth in the Ocean North Atlantic of Colombia.	From the simulation, several variables of interest such as torque, angular velocity, power, turbine efficiency, hydrokinetic and structural analysis were obtained in order to assess power generation.
[28] Tigabu et al.	Assessment of the theoretical hydrokinetic power and the	The developed model presents agreement with the

(2020) Ethiopia	potential use of hydrokinetic turbines in the river network in the Upper Blue Nile basin, and Koga irrigation canal, using computer simulations that based on key hydrologic, hydraulic and geometric parameters which are obtained from historical data and field visits. The Blue Nile is the most important basin due to accounts for 53% of the nation's water resource. The developed model was validated with measurements in the Gumara and Gilgel-Abay rivers of the Upper Blue Nile basin and the Koga irrigation canal.	measurements in the Gumara and Gilgel-Abay rivers and the Koga irrigation canal. This study shows: first, 25% of the Gumara river length is suitable for hydrokinetic turbines with a power capacity of 1.4 kW/m2; second, the 32% of the Gilgel-Abay river length has a maximum velocity above 1 m/s and capacity of 3.4 kW/m2; third, 29 % of the Bahirdar-Abay river length has a capacity of 2.6 kW/m2; finally, 100% main canal length of Koga human-made irrigation canal presents remarkable potential with a capacity of 4.3 kW/m2.
[29] Miller et al. (2011) Ghana	This research is focused on the site selection and the implementation of hydrokinetic power technology in the rural communities in the northern region of Ghana.	The flow rate, the amount of time for excessive or recessive flows and predictability and stability flow produces a decreasing flow rate less than a 70% compared with large and small hydropotential power.
[30] Kontoyiannis et al. (2015) Greece	Assessing the hydrokinetic energy from field measurements of tidal stream in a Euripus Strait channel.	The installed turbine yields an annual energy of 28.6 MWh, out of an existing 71.5 MWh for its aperture when there is zero efficiency loss. This amount of energy is not enough for wide-scale applications, but it covers the needs of an exhibition place.
[31] Saini et al. (2020) India	Assessment of the theoretical hydrokinetic power and the potential use of hydrokinetic turbine arrays in the main canal of Yamuna River, using analytical simulations that based on key hydrologic, hydraulic, geometric parameters and equipment technical data, which are obtained from historical data and manufacturers datasheet. These canals are usually designed to carry the water for irrigation purpose.	With a length of 195 Km of the Yamuna River main canal, a maximum hydrokinetic potential of 26.48 MW that correspond to velocity of 2.5 m/s, can be extracted with minimum 904 number of arrays. On the other hand, in a less favorable scenario is need 5650 number of arrays for a maximum potential of 10.59MW corresponding to 1.0 m/s of flow velocity.
[32] Dayyani et al. (2003) Iran	Geographic information system was used to estimate the physiographical characteristics, flow accumulation and flow directions of Gharahsoo watershed. The results were compared with measured data.	Geographic information system model is a faster and more accurate methodology compared to manual to calculations.
[33] Punys et al. (2015) Lithuania	Assessment of the theoretical hydrokinetic power and the potential use of hydrokinetic turbines in the Neris River, the second largest river in Lithuania, using computer simulations that based on key hydrologic, hydraulic and geometric parameters.	In a normal water year, the Neris River mean power density is 0.30 kW/m^2, and the mean power at a cross-section is 39 kW. There are around 20 sections where the power density exceeds 1 kW/m^2 and only 2 sections with more than 3 kW/m^2. In low flow conditions, the river's mean power density falls to 0.20 kW/m^2, and the mean power at a cross section is 22 kW.
[34] Zdankus et al. (2016) Lithuania	Evaluation of two hydrokinetic power plants working in two lowland rivers in Lithuania.	The insufficient velocities of the flow and limited resources of kinetic energy the lowland rivers containing water vegetation and suspended particles in water channels require special in-stream energy converters and technologies for their practical application.
[35] Ibrahim et al. (2019) Malaysia	Site investigation on the hydrokinetic potential at Pasir Kubur River, Kuantan (Malaysia).	The total annual energy yield can be achieved between 1.8 up to 4 MWh at the average water velocity of 1.1 m/s with 1.0 and 1.5 m^2 turbines swept area respectively
[36] Ladokun et al. (2018) Nigeria	Assessment of the potential and feasibility of increasing the hydropower production of Nigeria's three main hydropower stations by installing hydrokinetic turbines behind the existing dams.	Preliminary results showed that there are considerable potentials in the range of kilowatts and megawatts in each hydropower station to augment the existing power infrastructure.
[37] Kusakana et al. (2014) South Africa	A hybrid optimization model to simulate the hydrokinetic power to supply electricity in rural communities in the Eastern Cape, Mpumalanga and KwaZulu-Natal provinces in South Africa. Two case studies were conducted: rural household (The load was 3.4 kW peak and 9.5 kWh per day) and base transceiver station (the load was 7.1 kW peak and 58.8 kWh energy consumption per day). Some comparisons with diesel generator and photovoltaic and wind power were included.	According the technical and economical results based on criteria such as the initial capital, the net present cost, the cost of energy system capacity shortage and the breakeven grid extension distance was notice that the hydrokinetic is the best option to supply the load with electricity. The hydrokinetic system gives an average minimum output of 1 kW
[38] Kusakana (2013) South Africa	Techno-economic analysis of hydrokinetic-based hybrid systems in rural South Africa. Different hybrid configurations are simulated using the Hybrid Optimization Model for Electric Renewable (HOMER)	Hybrid systems with hydrokinetic modules have a lower net present costs and lower costs of energy compared to other supply options.
[39] Lalander et al. (2009) Sweden	In this study, the measurements of velocity, flow and water level in the Dalälven river were compared with numerical simulations for in-stream current energy converters.	It showed that 75 kW and 135 kW are extracted; the water level at the power station is increased in 5.5 and 8.8%, respectively, from the level without any turbines. Additionally, with increasing of the drag coefficient, the velocity decreases at the turbine while it increases around the turbine.
[40] Previsic et al. (2008) United States (Alaska)	Feasibility study of River In-Stream Energy Conversion (RISEC) for three Alaska rivers in isolated communities. The study is conducted by the Electric Power Research Institute.	This study shows that commercial scale economics is limited in the isolated villages. Small deployment scales will yield higher comparable cost, with a simple payback period (SPP) of at least 3 years.
[41] Ames et al. (2009) United States of	The geographic information system was used by estimation of stream channel geometry with based on drainage area, averaged precipitation, mean slope, elevation, forest cover	The model predicts that drainage area and precipitation have a primary effect on prediction of stream width and depth while slope and elevation watershed had a secondary effect.

America	and percent area of the watershed in Idaho Region.	
[7] Johnson and Pride (2010) United States of America (Alaska)	Two hydrokinetic turbines have been tested. A 5 kW turbine was set in operation at Ruby in 2008-2010 and a 25 kW turbine at Eagle in 2010.	The Eagle deployment was grid-connected. The floating and submerged debris adversely affected turbines performance and sometimes receive significant damage, therefore, a regular cleaning was required.
[42] Toniolo et al. (2010) United States of America (Alaska)	Assessment of the hydrokinetic potential of a reach of the Tanana river near Nenana, Alaska, is developed to help decide the suitability of the reach for installing and operating hydrokinetic electric turbines	Study results indicate that hydraulic conditions in the river reach may be suitable for turbine operations above the 800 m downstream location, with an average value for instantaneous power density of 4500 W/m^2 at the period of measurement (late August).
[43] Toniolo, 2012 United States of America (Alaska)	Hydrodynamic simulations were performed to estimate flow conditions and to assess the hydrokinetic potential of 2.5 km of the Kvichak River in southwest Alaska.	Study results indicate that an average velocity of 1.1m/s (upstream) generates approximately 1500 and 5500 W/m^2 during April and September while an average velocity around to 2 m/s (downstream) generates 400 and 2500 W/m^2 for the same months.
[44] Jacobson et al. (2012) United States of America	The assessment of the hydrokinetic resource in the 48 states of the USA derived from database with specific information on discharge characteristics and channel slope of 71,398 river segments with mean annual flow greater than 1,000 cubic feet per second)	According to the technical study, the segment-specific totaled 1381 TW/year. Lower Mississippi, Alaska, Pacific Northwest, and Ohio regions encompass 80% of the hydrokinetic resource reported in this study.
[45] Palodichuk et al. (2013) United States of America	Field measurements with Puget Sound for observing turbulence at tidal energy two sites turbulence in eastern of Marrowstone Island in, turbine Verdant power	The results exhibited intensity of turbulence are around 10% at the hub heights of the proposed turbines. Additionally, a good agreement between shipboard and bottom-mounted observations in capturing spatial trends of the hydrokinetic resource over a single tidal peak was observed
[46] Duerr et al. (2012) United States of America	The development of model and measurements from the Florida Current to assessment of the hydrokinetic energy resource of the Florida Current	According to the model, it was estimated that approximately 25 GW of hydrokinetic power is available in the Florida Current
[47] VanZwieten et al. (2013) United States of America	The development of a numeric simulation for modeling a 20-kW experimental ocean current turbine, for environmental in the gulf stream off southeast Florida	A maximum rotor power coefficient of 0.45 was predicted for the model; additionally, the vertical current gradient will only minimally affect the system performance
[48] Muljadi and Yu (2015) United States of America	Review of Marine Hydrokinetic Power Generation (MHK) and potential for the U.S.	MHK renewable energy has a great potential to provide a significant contribution to the electricity supply. However, MHK technology is still emerging, and the cost of energy is not yet competitive with other forms of renewable energy. The cost of the power take-off represents approximately 10–20% of the overall cost of energy and has a great influence on the power generation performance.
[49] Gunawan et al. (2017) United States of America	Report in collaboration with the U.S. Bureau of Reclamation and Sandia National Laboratories reviewing the main considerations and assessment methods for implementing field tests in open-channel water systems. the Roza Main Canal, in Yakima, WA. U.S.A. is taken as a case study.	For a feasibility level study, bathymetry, discharge, and water level data at key locations of the channel (transitions, bifurcations, siphons, flow measurement structures, etc.) are sufficient to help decide if hydrokinetic deployment is a choice. These data can be used with numerical models to support studies.
[50] Edgerly and Ravens (2019) United States of America (Alaska)	Study of the hydraulic effect of hydrokinetic energy extraction in the Tanana River, Alaska.	Measurements showed velocities being 97.8% recovered within 18.1 turbine diameters and fully recovered within 20.7 turbine diameters. ADV measurements also indicate a 520% increase in turbulence intensity at 2.6 turbine diameters downstream which appeared to resolve within 20.7 turbine diameters.
[51] Guerra and Thomson (2019) United States of America (Alaska)	Experimental study on field observations of the wake from a full-scale ORPC RivGen hydrokinetic turbine in the Kvichak River, which has approximately 5 m deep, 150 m wide and a maximum flow in the center of 2.5 m/s.	This work provides observations, analysis and a comprehensive data set of a full-scale cross-flow turbine wake, which can serve for validation of numerical models and future turbine array designs. On the other hand, these results can help to the turbine designers, project developers and decision makers about the environmental impacts of hydrokinetic systems.
[52] D'Auteuil et al. (2019) United States of America (Alaska)	In this work, a method base on the use of available winter imagery to improve the site selection in a river for the installation of a hydrokinetic turbine is proposed. This method is applied to the Winnipeg River, which has satellite imagery during frozen months. Furthermore, it is experimentally validated with measurements in situ of the river flow and turbulence quantities.	The method is low cost. The study shown that the Winnipeg River sections that do not freeze during the winter have higher velocity magnitudes (average velocity magnitude of 1.09 m/s) than sections that are covered with ice (average velocity magnitude of 0.301 m/s).
[53] Lust et al (2021) United States of America	This study is focused on study the impact of wave motion over the quantity and quality of power produced by H-Darrieus cross-flow hydrokinetic turbine. A scale 1:6 model was probed in a tank at the United Stated Naval Academy.	According reported experimental results, the waves amplify or diminish the cyclic signatures in the power measurement as function of the phase difference between the blade angle and wave phase angle. Additionally, the use of active control strategies improves the power quality.

Source: Elaborated by the authors

4. Conclusions

It is clear the world interest in taking advantage of all the energy potential that many countries have at river and marine level, even more so with the constantly growing demand for energy and especially clean energy in accordance with the policies and purposes oriented by The Sustainable Development Goals (SDGs), in addition to the immersed benefits in economic and social development.

Although years ago, hydrokinetic generation in rivers was not considered a feasible option to implement in off-grid power generation, in the last decade interest in this technology has given rise to intense exploration around the world, with initiatives to evaluate and adjust the technical and economic aspects to an adequate adoption, seeking to satisfy, first and foremost, the needs of isolated communities. The challenges inhibiting its development have been associated with the lack of previous research demonstrating the technical, economic and environmental benefits, what can be achieved through the implementation of techno-economic analyses that include the cost of capital, the definition of the most suitable location for installation, maintenance and operation.

An interesting alternative that can be considered as a pilot of hydrokinetic projects is the deployment of turbines for power generation downstream of hydropower plants. Several initiatives in this regard have been reported, including Brazil and a first initiative in Colombia in 2016 [21] in a pre-feasibility stage, showing that it requires further development and studies for optimal benefit.

In Colombia, very little research and development of pilot projects for the use of hydrokinetic technology has been reported, despite the great potential of the country and the enormous needs of a large number of riverside populations, outside the coverage of electricity distribution networks. Additionally, at the governmental level, no specific policies or programs have been established to develop hydrokinetic energy projects, beyond a general promotion of non-conventional sustainable energies for the next decades, among which the potential of small hydroenergy uses is considered [54]. However, research proposals are being advanced by some research groups in collaboration with development centers and industries at the forefront of this technology, to implement energy solutions for this type of populations that require this type of innovative solutions, bearing in mind that this type of project requires an intervention of a social nature for its adequate adoption and permanence in time.

Acknowledgment

The authors are grateful to the project: Identification of Knowledge Gaps in the Academy and Capacity Building for Aquatic Renewable Energy in Colombia, sponsored by the Universidad Cooperativa de Colombia under projects numbers INV2309, and the Royal Academy of Engineering/Newton Fund under grant number IAPP1\100166.

References

[1] Ediger, V.Ş., An integrated review and analysis of multi-energy transition from fossil fuels to renewables. Energy Procedia, 156, pp. 2-6, 2019. DOI: 10.1016/j.egypro.2018.11.073.

[2] Bueno-Lopez, M. and Garzon-Lemos, S., Electrification in Non-interconnected areas: towards a new vision of rurality in Colombia. IEEE Technology and Society Magazine, 36(4), pp. 73-79, 2017. DOI: 10.1109/MTS.2017.2763479.

[3] Hil-Baky, M.A., Rahman, M.M. and Islam, A.K.M.S., Development of renewable energy sector in Bangladesh: current status and future potentials. Renewable and Sustainable Energy Reviews, 73, pp. 1184-1197, 2017. DOI: 10.1016/j.rser.2017.02.047.

[4] Yuce, M.I. and Muratoglu, A., Hydrokinetic energy conversion systems: a technology status review. Renewable and Sustainable Energy Reviews, 43, pp. 72-82, 2015. DOI: 10.1016/j.rser.2014.10.037.

[5] Chandel, S.S., Shrivastva, R., Sharma, V. and Ramasamy, P., Overview of the initiatives in renewable energy sector under the national action plan on climate change in India. Renewable and Sustainable Energy Reviews, 54, pp. 866-873, 2016. DOI: 10.1016/j.rser.2015.10.057.

[6] Vermaak, H.J., Kusakana, K. and Koko, S.P., Status of micro-hydrokinetic river technology in rural applications: a review of literature. Renewable and Sustainable Energy Reviews, 29, pp. 625-633, 2014. DOI: 10.1016/j.rser.2013.08.066.

[7] Johnson, J.B. and Pride, D.J., River, tidal and ocean current hydrokinetic energy technologies: status and future opportunities in Alaska, 2010.

[8] Ardizzon, G., Cavazzini, G. and Pavesi, G., A new generation of small hydro and pumped-hydro power plants: advances and future challenges. Renewable and Sustainable Energy Reviews, 31, pp. 746-761, 2014. DOI: 10.1016/j.rser.2013.12.043.

[9] Miller, V.B., Landis, A.E. and Schaefer, L.A., A benchmark for life cycle air emissions and life cycle impact assessment of hydrokinetic energy extraction using life cycle assessment. Renewable Energy, 36(3), pp. 1040-1046, 2011. DOI: 10.1016/j.renene.2010.08.016.

[10] Taylor, G.W., Burns, J.R., Kammann, S.A., Powers, W.B. and Welsh, T.R., The energy harvesting eel: a small subsurface ocean/river power generator. IEEE Journal of Oceanic Engineering, 26(4), pp. 539-547, 2001. DOI: 10.1109/48.972090.

[11] Khan, M.J., Bhuyan, G., Iqbal, M.T. and 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, 86(10), pp. 1823-1835, 2009. DOI: 10.1016/j.apenergy.2009.02.017.

[12] Behrouzi, F., Maimun, A. and Nakisa, M., Review of various designs and development in hydropower turbines. World Academy of Science, Engineering and Technology, Open Science Index 86, International Journal of Mechanical and Mechatronics Engineering, 8(2), pp. 293-297, 2014.

[13] Kumar, A. and Saini, R.P., Performance parameters of Savonius type hydrokinetic turbine - A review. Renewable and Sustainable Energy Reviews, 64, pp. 289-310, 2016. DOI: 10.1016/j.rser.2016.06.005.

[14] Sørnes, K., Small-scale water current turbines for river applications. 2010.

[15] Saini, G. and Saini, R.P., A review on technology, configurations, and performance of cross-flow hydrokinetic turbines. International Journal of Energy Research, 43 pp. 6639- 6679, 2019. DOI: 10.1002/er.4625.

[16] Rourke, F.O., Boyle, F. and Reynolds, A., Marine current energy devices: current status and possible future applications in Ireland. Renewable and Sustainable Energy Reviews, 14(3), pp. 1026-1036, 2010. DOI: 10.1016/j.rser.2009.11.012.

[17] Lago, L.I., Ponta, F.L. and Chen, L., Advances and trends in hydrokinetic turbine systems. Energy for Sustainable Development, 14(4), pp. 287-296, 2010. DOI: 10.1016/j.esd.2010.09.004.

[18] Kirke, B.K., Tests on ducted and bare helical and straight blade Darrieus hydrokinetic turbines. Renewable Energy, 36(11), pp. 3013-3022, 2011. DOI: 10.1016/j.renene.2011.03.036.

[19] van Els, R.H. and Brasil Junior, A.C.P., The Brazilian Experience with hydrokinetic turbines. Energy Procedia, 75, pp. 259-264, 2015. DOI: 10.1016/j.egypro.2015.07.328.
[20] Holanda, P. da S., Blanco, C.J.C., Mesquita, A.L.A., Brasil Junior, A.C.P., de Figueiredo, N.M., Macêdo, E.N., et al., Assessment of hydrokinetic energy resources downstream of hydropower plants. Renewable Energy, 101, pp. 1203-1214, 2017. DOI: 10.1016/j.renene.2016.10.011.
[21] Montoya-Ramírez, R.D., Cuervo, F.I. and Monsalve Rico, C.A., Technical and financial valuation of hydrokinetic power in the discharge channels of large hydropower plants in Colombia: a case study. Renewable Energy, 99, pp. 136-147, 2016. DOI: 10.1016/j.renene.2016.06.047.
[22] Ulvmyr, A., Potential risks and prospects of protections of a hydrokinetic turbine implemented in the Amazon River, Colombia: a theoretical and practical study. Karlstad University, MSc. Thesis, 2016.
[23] Ramirez-Tovar, A.M., López, Y.U. and Laín, A.M., Design and prototype of a micro hydrokinetic vertical turbine. Renewable Energy and Power Quality Journal, 1(15), pp. 903-910, 2017. DOI: 10.24084/repqj15.512.
[24] Arrieta, E.L.C., Cardona-Mancilla, C., Slayton, J., Romero, F., Torres, E., Agudelo, S., et al., Experimental investigations and CFD simulations of the blade section pitch angle effect on the performance of a horizontal-axis hydrokinetic turbine. Engineering Journal, 22(5), pp. 141-154, 2018. DOI: 10.4186/ej.2018.22.5.141.
[25] Chica, E., Torres, E.A. and Arbeláez, J., Manufacture and experimental evaluation of a hydrokinetic turbine for remote communities in Colombia. Renewable Energy and Power Quality Journal, 1, pp. 82-87, 2018. DOI: 10.24084/repqj16.217.
[26] Ramirez-Tovar, A.M., López-Castrillón, Y.U. and Laín, S., Simulating and designing small hydrokinetic turbines: a review. International Review of Mechanical Engineering (IREME), 12(11), pp. 876, 2018. DOI: 10.15866/ireme.v12i11.15525.
[27] Fabregas-Villegas, J., Santamaria-de la Cruz, H., Márquez-Santos, M., Fontalvo-Calvo, C., Carpintero-Durango, J. and Villa-Dominguez, J., Design of a hydrokinetic turbine capable of satisfying electricity demand for housing on the margin of the Magdalena River through analysis by finite elements. International Journal of Engineering Science, 7(4), pp. 6848-6850, 2018. DOI: 10.14419/ijet.v7i4.26843.
[28] Tigabu, M.T., Wood, D.H. and Admasu, B.T., Resource assessment for hydro-kinetic turbines in Ethiopian rivers and irrigation canals. Energy for Sustainable Development, 58, pp. 209-224, 2020. DOI: 10.1016/j.esd.2020.08.005.
[29] Miller, V.B., Ramde, E.W., Gradoville, R.T. and Schaefer, L.A., Hydrokinetic power for energy access in rural Ghana. Renewable Energy, 36(2), pp. 671-675, 2011. DOI: 10.1016/j.renene.2010.08.014.
[30] Kontoyiannis, H., Panagiotopoulos, M. and Soukissian, T., The Euripus tidal stream at Halkida/Greece: a practical, inexpensive approach in assessing the hydrokinetic renewable energy from field measurements in a tidal channel. Journal of Ocean Engineering and Marine Energy, 1(3), pp. 325-335, 2015. DOI: 10.1007/s40722-015-0020-8.
[31] Saini, G., Kumar, A. and Saini, R.P., Assessment of hydrokinetic energy - A case study of eastern Yamuna canal. Materials Today: Proceedings, 2020. DOI: 10.1016/j.matpr.2020.08.595.
[32] Dayyani, S., Mohammadi, K. and Reza-Najib, H., River flow estimation for ungaged stations using GIS model. 7th Int. Water Technol. Conf., Egypt: 2003, pp. 347-355.
[33] Punys, P., Adamonyte, I., Kvaraciejus, A., Martinaitis, E., Vyciene, G. and Kasiulis, E., Riverine hydrokinetic resource assessment. a case study of a lowland river in Lithuania. Renewable and Sustainable Energy Reviews, 50, pp. 643-652, 2015. DOI: 10.1016/j.rser.2015.04.155.
[34] Zdankus, N., Punys, P. and Zdankus, T., Conversion of lowland river flow kinetic energy. Renewable and Sustainable Energy Reviews, 38, pp. 121-130, 2014. DOI: 10.1016/j.rser.2014.05.074.
[35] Ibrahim, W.I., Ismail, R.M.T.R. and Mohamed, M.R., Micro-Hydro energy estimation for hydrokinetic energy harnessing at Sungai Lembing, Conference or Workshop, TK Electrical engineering. Electronics Nuclear engineering, 2019, pp. 549-562. DOI: 10.1007/978-981-13-3708-6_49.
[36] Ladokun, L.L., Sule, B.F., Ajao, K.R. and Adeogun, A.G., Resource assessment and feasibility study for the generation of hydrokinetic power in the tailwaters of selected hydropower stations in Nigeria. Water Science, 32(2), pp. 338-354, 2018. DOI: 10.1016/j.wsj.2018.05.003.
[37] Kusakana, K. and Vermaak, H.J., Hydrokinetic power generation for rural electricity supply: case of South Africa. Renewable Energy, 55, pp. 467-473, 2013. DOI: 10.1016/j.renene.2012.12.051.
[38] Kusakana, K., Techno-economic analysis of off-grid hydrokinetic-based hybrid energy systems for onshore/remote area in South Africa. Energy, 68, pp. 947-957, 2014. DOI: 10.1016/j.energy.2014.01.100.
[39] Lalander, E. and Leijon, M., Numerical modeling of a river site for in-stream energy converters. 8th Eur. Wave Tidal Energy Conf., Uppsala, Sweden: 2009, pp. 826-832.
[40] Previsic, M., Bedard, R. and Polagye, B., System level design, performance, cost and economic assessment—Alaska River in-stream power plants. Report EPRI RP 006, Washington, D.C., USA, 2008.
[41] Ames, D.P., Rafn, E.B., Van Kirk, R. and Crosby, B., Estimation of stream channel geometry in Idaho using GIS-derived watershed characteristics. Environmental Modelling & Software, 24(3), pp. 444-448, 2009. DOI: 10.1016/j.envsoft.2008.08.008.
[42] Toniolo, H., Duvoy, P., Vanlesberg, S. and Johnson, J., Modelling and field measurements in support of the hydrokinetic resource assessment for the Tanana river at Nenana, Alaska. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 224(8), pp. 1127-1139, 2010. DOI: 10.1243/09576509JPE1017.
[43] Toniolo, H., Hydrokinetic assessment of the Kvichak River near Igiugig, Alaska, using a two-dimensional hydrodynamic model. Energy and Power Engineering, 04(06), pp. 422-431, 2012. DOI: 10.4236/epe.2012.46056.
[44] Jacobson, P., Assessment and mapping of the riverine hydrokinetic resource in the continental United States. 2012. DOI: 10.2172/1219876.
[45] Palodichuk, M., Polagye, B. and Thomson, J., Resource mapping at tidal energy sites. IEEE Journal of Oceanic Engineering, 38(3), pp. 433-446, 2013. DOI: 10.1109/JOE.2012.2227578.
[46] Duerr, A.E.S. and Dhanak, M.R., An assessment of the hydrokinetic energy resource of the Florida current. IEEE Journal of Oceanic Engineering, 37(2), pp. 281-293, 2012. DOI: 10.1109/JOE.2012.2186347.
[47] VanZwieten, J.H., Vanrietvelde, N. and Hacker, B.L., Numerical simulation of an experimental ocean current turbine. IEEE Journal of Oceanic Engineering, 38(1), pp. 131-143, 2013. DOI: 10.1109/JOE.2012.2218891.
[48] Muljadi, E. and Yu, Y.-H., Review of marine hydrokinetic power generation and power plant. Electric Power Components and Systems, 43(12), pp. 1422-1433, 2015. DOI: 10.1080/15325008.2015.1030519.
[49] Gunawan, B., Assessing and testing hydrokinetic turbine performance and effects on open channel hydrodynamics: an irrigation canal case study. Report SAND2017-4925R, Albuquerque, NM, USA,2017.
[50] Edgerly, E.M. and Ravens, T.M., Measuring the hydraulic effect of hydrokinetic energy extraction in the Tanana River, Alaska. Journal of Ocean Engineering and Marine Energy, 5(3), pp. 241-250, 2019. DOI: 10.1007/s40722-019-00142-x.
[51] Guerra, M. and Thomson, J., Wake measurements from a hydrokinetic river turbine. Renewable Energy, 139, pp. 483-495, 2019. DOI: 10.1016/j.renene.2019.02.052.
[52] D'Auteuil, S., Birjandi, A., Bibeau, E., Jordan, S., Soviak, J. and Friesen, D., Riverine hydrokinetic resource assessment using low cost winter imagery. Renewable and Sustainable Energy Reviews, 105, pp. 293-300, 2019. DOI: 10.1016/j.rser.2019.01.057.
[53] Lust, E.E., Bailin, B.H. and Flack, K.A., Performance characteristics of a cross-flow hydrokinetic turbine in current only and current and wave conditions. Ocean Engineering, 219, pp. 108362, 2021. DOI: 10.1016/j.oceaneng.2020.108362.
[54] Unidad de Planeación Minero Energética (UPME), Plan Energetico Nacional Colombia: Ideario Energético 2050. Republica de Colombia, pp. 184, 2015.

V.H. Aristizabal-Tique, obtained his BSc. Eng. in Physical Engineering in 2004, from the Universidad Nacional de Colombia in Medellin and the MSc. in Physics in 2008 from the same university. He is currently doctoral student at EAFIT University and full-time research-professor at the Cooperative University of Colombia, Medellín, Colombia. His work has been focused on analytical and computational modeling of the elastic waves in seismic engineering and geophysical prospecting, and electromagnetic waves in optical communications and sensing.
ORCID: 0000-0002-7880-5883

A.P. Villegas-Quiceno, is a BSc. Eng. in Chemical Engineer from the Universidad Nacional de Colombia, Medellín campus, MSc. in Engineering in 2012, PhD. in Chemical Engineering in 2017, all of them from the Universidad de Antioquia, Medellin, Colombia. Currently is Dean of Faculty of the Engineering at the Cooperative University of Colombia, in Medellín. Her research work has been focused on the modelling, simulation and optimization of the mechanical, chemical and biotechnological processes.
ORCID: 0000-0001-9697-8297

O.F. Arbeláez-Pérez, is BSc. Eng. in Chemical Engineer in 2004, and the MSc. in Chemical Sciences in 2009, all of them from the Universidad Nacional de Colombia, Medellin campus, obtained his PhD. in Engineering in 2015, from the Universidad de Antioquia Medellin, Colombia. Currently is full-time research-professor at the Universidad Cooperativa de Colombia, Medellin, Colombia. His research work has been focused on the synthesis, characterization and evaluation of catalysts for abatement of pollutant emissions and on the preparation and evaluation of physical and mechanical properties of concretes and construction materials.
ORCID: 0000-0001-8592-5333

Ramón F. Colmenares-Quintero, he is currently national head of research in engineering and Professor Dr. at the Universidad Cooperativa de Colombia (UCC) with research focus on energy generation, simulation and modelling in the energy sector and multi-objective optimisation for renewable-energy systems and sustainable communities.
ORCID: 0000-0003-1166-1982

Francisco J. Vélez-Hoyos, received his B.S. degree in Physical Engineering from National University of Colombia in Medellin in 2004 and the M.Sc. in Physics in 2008 from the same university. He is currently doctoral candidate at Eafit University and full-time Research-Professor at the Cooperative University of Colombia, Medellín, Colombia. His work has been oriented to computational modeling in applied optics, sensors and elastic waves on nonclassical media.
ORCID: 0000-0002-4267-042X