Vol. 22, n.°3, pp. 39-54, 2023
Revista UIS Ingenierías
Página de la revista: https://revistas.uis.edu.co/index.php/revistauisingenierias

Gravitational water vortex hydraulic turbine implementation in Colombia: hydropower potential and prospects

Implementación de una turbina hidráulica de vórtice de agua gravitacional en Colombia: potencial hidroeléctrico y perspectivas

Laura Velásquez [1a], Ainhoa Rubio-Clemente [1b, 2], Alejandro Posada [3], Edwin Chica [1c]

[1] Grupo de Investigación Energía Alternativa (GEA), Facultad de Ingeniería, Universidad de Antioquia, Colombia. Orcid: 0000-0003-1483-0104 [a], 0000-0003-1527-260X [b], 0000-0002-5043-6414 [c]. Email: lisabel.velasquez6@udea.edu.co [a], ainhoa.rubioc@udea.edu.co [b], edwin.chica@udea.edu.co [c]
[2] Escuela Ambiental, Facultad de Ingeniería, Universidad de Antioquia, Colombia.
[3] Grupo de Investigación e Innovación Ambiental, Facultad de Ingeniería, Institución Universitaria Pascual Bravo, Colombia. Orcid: 0000-0001-5836-0680. Email: alejandro.posada@pascualbravo.edu.co

Received: 13 October 2022. Accepted: 12 May 2023. Final version: 21 June 2023.

Abstract

The availability of the energy has changed the humanity over the last centuries. The first types of energy used by humanity were renewable energies: biomass, wind, and water. But, for the last two centuries, fossil fuels have been the protagonists of world energy consumption. However, recently there has been an awareness of the great energy dependence on a finite resource, geographically concentrated in a few countries, which in addition to degrading the environment, is subject to large fluctuations in price. From renewable energies, hydroelectricity is currently the most important source in the Latin American electricity matrix. Current projections suggest that the installed hydroelectric capacity will continue to grow to meet future electricity demand. New turbine designs, such as gravitational water vortex hydraulic turbines, have drawn the attention of many researchers due to their easy installation and maintenance, and their low environmental impact. This work presents the hydropower potential and prospects for the implementation of this type of turbine in the Colombian context, and as well as a general description of the current panorama of the Colombian energy system.

Keywords: Colombia; electricity consumption; energy; environmental impact; fossil fuel; Gravitational water vortex hydraulic turbine; hydropower generation; natural resources; renewable energy; small hydropower plant.

Resumen

La disponibilidad de la energía ha cambiado a la humanidad en los últimos siglos. Los primeros tipos de energía utilizados por la humanidad fueron las energías renovables: la biomasa, el viento y el agua. Pero, desde hace dos siglos, los combustibles fósiles han sido los protagonistas del consumo energético mundial. Sin embargo, recientemente se ha tomado conciencia de la gran dependencia energética de un recurso finito, concentrado geográficamente en unos pocos

ISSN Printed: 1657 - 4583, ISSN Online: 2145 - 8456.

How to cite: L. Velásquez, A. Rubio-Clemente, A. Posada, E. Chica, "Gravitational water vortex hydraulic turbine implementation in Colombia: hydropower potential and prospects," *Rev. UIS Ing.*, vol. 22, no. 3, pp. 39-54, 2023, doi: https://doi.org/10.18273/revuin.v22n3-2023004

países, que además de degradar el medio ambiente, está sujeto a grandes fluctuaciones de precio. De las energías renovables, la hidroelectricidad es actualmente la fuente más importante de la matriz eléctrica latinoamericana. Las proyecciones actuales sugieren que la capacidad hidroeléctrica instalada seguirá creciendo para satisfacer la futura demanda de electricidad. Los nuevos diseños de turbinas, como las turbinas hidráulicas de vórtice de agua gravitacional, han llamado la atención de muchos investigadores debido a su fácil instalación y mantenimiento, y su bajo impacto ambiental. Este trabajo presenta el potencial hidroeléctrico y las perspectivas de implementación de este tipo de turbinas en el contexto colombiano, así como una descripción general del panorama actual del sistema energético colombiano.

Palabras clave: Colombia; consumo de electricidad; energía; impacto medioambiental; combustible fósil; Turbina hidráulica de vórtice de agua gravitacional; generación hidroeléctrica; recursos naturales; energía renovable; pequeña central hidroeléctrica.

1. Introduction

Throughout the human prehistory and history, several sources of energy have been used worldwide, from the human own-self strength to the energy generated in a water wheel for smashing grains and fruits [1]. However, for last two centuries, fossil fuels continued to be the protagonist of the world energy consumption although it is a finite resource that is geographically concentrated in a few countries, damage the environment, and is subjected of speculation in international markets [2], [3].

For all this, most of the measures taken in relation to energy are aimed at curbing consumption, increasing efficiency and diversification by committing to renewable energies. An interesting option for the generation and employing renewable energy, specifically hydropower energy, is the gravitational water vortex hydraulic turbine (GWVHT). These turbines operate at flow rates of 0.05–5 m^3/s and hydraulic heads between 0.5 and 2.0 m [4].

The hydraulic head is considered too low for conventional hydroelectric turbines. Francis, Pelton, and crossflow turbines are incompatible when the hydraulic head is less than 3 m [5]. It was found that GWVHT, due to its ability to sustain relatively high efficiencies at low heads and small to medium flow rates, addresses a gap in the current turbine application chart [6]. Compared to traditional large-scale hydroelectric systems, GWVHT has a much lower impact on the ecosystem as construction of a large dam is not necessary. Only a fraction of the river flow is diverted and passes through the system, and all water is returned downstream to the river [7]. The system also demonstrates potential to be able to function as a fish passage [6].

The current work focuses on the implementation of a GWVHT in developing countries, such as Colombia. The implementation of this type of turbine was analyzed through technical, economic, and environmental perspectives. The work is organized as follows: a count of the evolution of energy sources along the prehistory and history, followed by an analysis of energy consumption in the world, especially in Colombia. Next, a description of the operation of a gravitational water vortex hydraulic turbine and its advantages and its advantages; and finally, an analysis of the barriers and opportunities hydropower development in Colombia.

2. Evolution of energy sources along the prehistory and history

For a primitive man, well-being was linked to satisfying his need to feed himself daily through hunting and gathering. For this purpose, the only energy source was that derived from his own muscular strength [8]. 500,000 years ago, with the discovery of fire [9] derived from wood as the first fuel, a fundamental step was made in the use of energy, which represents a turning point in the evolution of the humanity. As the human population increased, the use of fire intensified, leading to the agriculture rise and domestication of animals. This resulted in the inclusion of animal strength as another energy source. Over the centuries, means of transportation on lakes, rivers and seas were developed, and the wind acting on fabric sails was widely used to propel boats [10].

Nevertheless, due to wind direction and power, the wind energy was combined with human muscular energy. Later, the energy of water began to be used, thanks to the invention of the water wheel, as a source of energy. This energy was used to turn stones or millstones [11]. Around 1180, wind energy found an important application in Europe when it began to be used to move the grinding wheels of grain mills [12], when other sources of energy, such as hydraulics, were difficult to be exploited.

With the use of hydraulic power, animal power and energy from burning wood, mining, metallurgy and other industrial activities were developed [13]. Due to the disproportionate increase in wood burning during the Middle Ages and the Renaissance, from the 17th century, there was a shortage of wood in Western Europe [14]. England began burning mineral coal as the main source of energy, but it was considered dirty and harmful to health [15], [16]. Coal was the most used fuel par excellence in developed countries until it gave way to oil in the 20th century. The invention of the steam engine, in the 18th century, was the first great modern energy invention [17].

Thanks to this, a means of mechanical energy production was available that made it possible to obtain high powers and was less geographically limited than the resources previously used. This invention was a banner of the First Industrial Revolution [18].

In 1729, the first studies on electricity began. The first electric battery dates to 1800, when Volta invented the first electrochemical generator capable of producing an electric current maintained over time [19]. In 1821, Faraday's first electric motor appeared [20], and in 1881, Thomas Alva Edison's invented the incandescent lamp [21].These kinds of energy sources, along with the water wheels, resulted in the increase in the current hydraulic turbines, and with them, the production of electricity. However, electrical energy, as a widely used energy, did not reach most of the population of developed countries until the first third of the 20th century [22]. In 1863 and 1885, with the invention of the internal combustion engine [23] and the automobile [24], respectively, the accelerated use of oil and its derived fuels began. Afterwards, the use of this type of energy spreads in the navy, in steam generators, in industrial ovens and in-home heating; today, oil represents the main source of energy in the world [25] despite its non-renewable character. Later, the first types of energy used by humanity were then renewable energies, including biomass, wind, sun, and water [26]. Nowadays, the use of renewable energy sources is in the target of both developed and developing countries around the world, especially in the former ones due to the negative environmental and health impacts associated with the use of fossil fuels.

3. Energy in the world and in the particular case of Colombia

The annual global energy consumption is estimated as 13,865 million tons of oil equivalents (Mtoe), or about 580 million TJ [27]. By 2040, global energy consumption will reach 740 million TJ – equivalent to additional 30% growth. The United States and China, with 2040 and 3381 Mtoe, respectively, are the countries with the highest energy consumption [28]. Figure 1 shows the percentage of electricity generation by fuel and region in 2020.

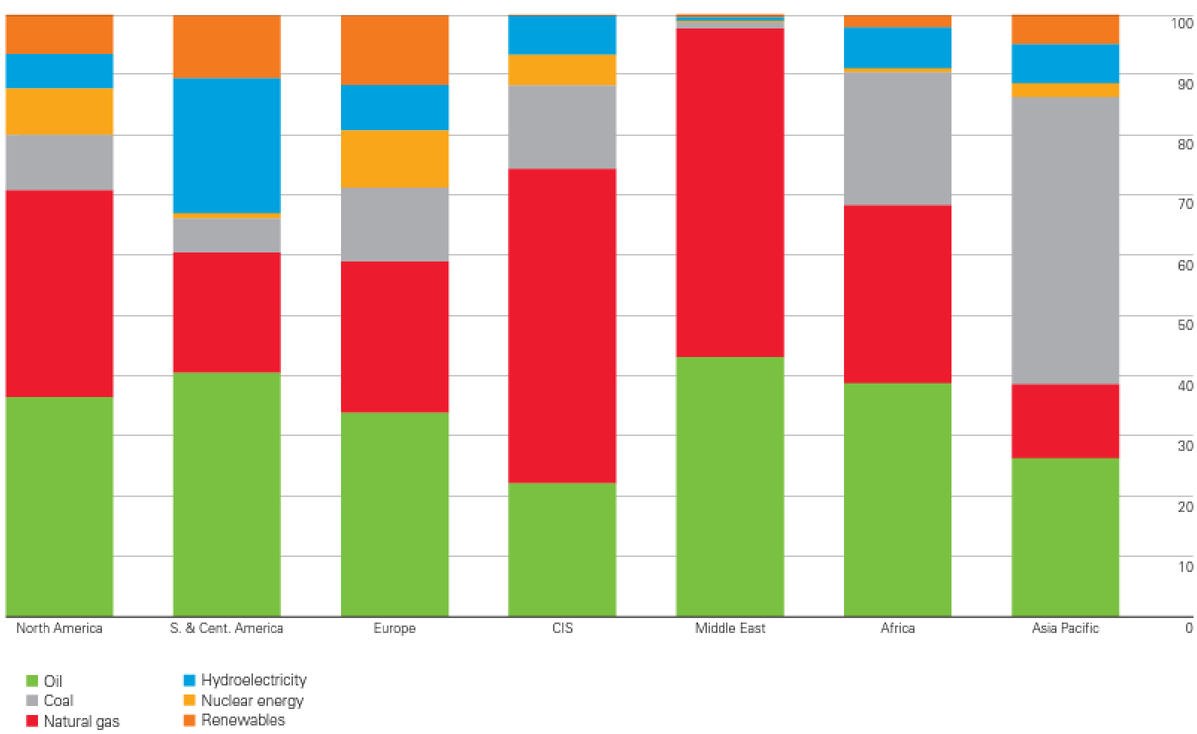

Figure 1. The percentage of electricity generation by fuel and region in 2020. Adapted from: [29].

According to Figure 1, natural gas is the dominant fuel used for power generation in Africa, North America, the Middle East and CIS (Commonwealth of Independent States). In turn, in Asia, coal comprises 57% of the generation mix, while 58% of the power in South and Central America is hydroelectricity and renewables. Of 58%, 77% of the electricity produced corresponds to the derived from hydroelectric plants, followed by wind and solar generation that together add up to 13%, 9% biomass, and 1% geothermal. Currently, the region has about 200,000 MW of installed hydropower capacity, of which 25,000 MW have been added in the last 5 years.

3.1. Electricity generation and provision in Colombia

Colombia is the fourth country in South America with the largest installed capacity in hydroelectricity, closely followed by Argentina and Venezuela, but very far from the first producer, Brazil, with an installed capacity of 110,000 MW [30], [31]. Colombia has an installed capacity of approximately 19,000 MW, of which 68.4% is generated from hydroelectric plants, 30.7% corresponding to thermal plants, and 1% to other renewable energy sources [32], [33], [34]. Brazil produces 62.9% of its electricity through hydropower [35]. Figure 2 shows the evolution of electricity production by source in Colombia between 2000 and 2020.

As observed in the Figure, hydropower is the main source in Colombia producing energy. It is important to note that hydroelectric power plants are essential for the sustainable development of the region's electrical matrix, not only because of the renewable energy supply they provide, but also because of the technological capacity to provide other services, such as flexibility and peak generation, frequency regulation, energy storage, among others, which currently allow the massive incorporation of intermittent generation sources (as solar and wind).

For this reason, the advances that can be achieved in the regulatory frameworks so that they adequately recognize the value of all services that hydroelectric plants provide to the system, beyond energy, will be essential to encourage investments not only the development of new hydroelectric projects, but also to accelerate the modernization of the existing hydroelectric power plants, essential to accompany the transformation toward low-carbon generation and its sustainability.

For years, hydroelectric plants have been considered synonymous of development. Colombia, owing to its topography, rainfall and water resources, has an exceptionally high potential to develop this type of engineering projects. In fact, Colombia has been classified as the second country in Latin America with the largest hydraulic capacity. The country has a flow among its main rivers of 52;075 m^3/s, and the water supply is 6 times higher than the world average. In hydroelectric power plants, their construction is less expensive than nuclear plants. Additionally, the operation is cheaper than thermoelectric plants, energy can be provided on a large or small scale, and low emissions of greenhouse gases (GG) are generated.

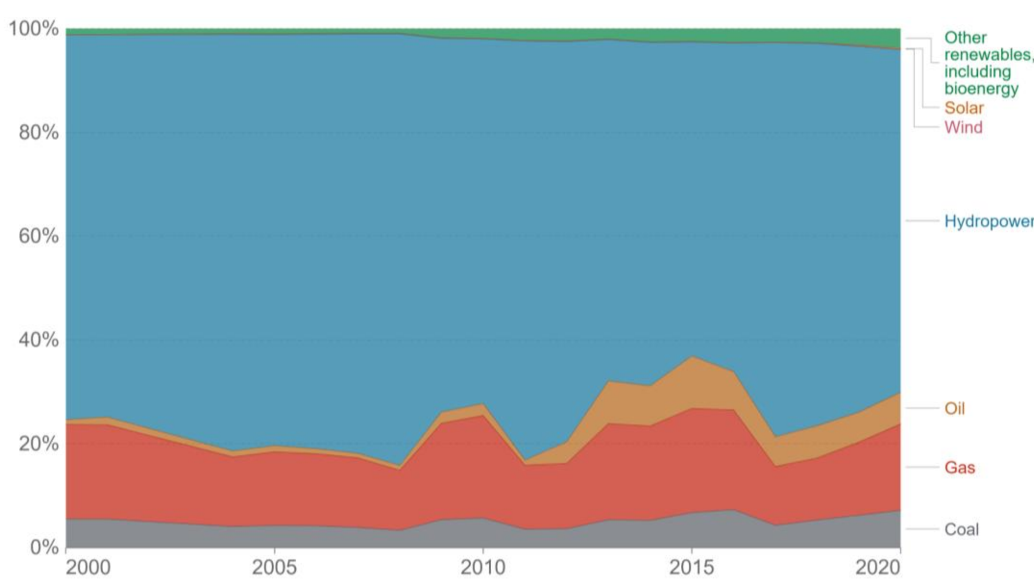

Figure 2. Electricity production by source, Colombia [36].

Large or small scales refers to the generated power. A large hydropower plant produces 10 MW or more, whereas a small hydropower plant (SHP) produces less of 10 MW [37]. A small hydropower plant is divided into further categories depending on its size, such as mini- (less than 1,000 kW), micro-hydro (less than 100 kW) and pico-hydro (less than 5kW). The definitions may vary according to manufacturers and countries [38].

The above reasons are sufficient that decision-makers at the state level have considered the construction of hydroelectric plants on important tributaries of the country, such as Alto Chicamocha, Betania, Calima, Chivor, Guavio, El Quimbo, Hidromiel, Hidrosogamoso, Ituango, Peñol-Guatapé, San Carlos, among others [31].

However, the construction and maintenance of large hydroelectric power plants mean an undeniable environmental, social and economic costs. Small-hydraulic power plants bring a great deal of research consideration. SHP is characterized by varying flows, low-head and highly valued river functions, including sediment transport, fish preservation and recreational usage, etc. [39], [40], [41].

According to the National Energy Plan, in SHP, Colombia has a potential of 25;000 MW. Despite this great power, 0.67% in SHP has been exploited. Several sites of small hydro-energy potential remain untapped due to the limitations of the hydraulic head besides the requirement of large flow rates for the power generation.

This potential energy resource can be used if new-innovative turbines that balance efficiency, economics and environmental sustainability are developed [42]. The supply of electrical energy, with a commercial approach, began in Colombia by private initiative at the end of the 19^{th} century, when the Bogotá Electric Light Company was created in 1888.

In the following years, also driven by private initiative, generation-distribution systems were developed in isolation in the main cities of the country [43].

Nowadays, the provision of electricity service and its expansion are carried out through the physical connection of users to the National Interconnected System (or SIN, by its acronym in Spanish). The geographical areas that are not electrically coupled to the SIN, are called Noninterconnected Zones (NIZ, ZNI in Spanish). NIZ do not have access to the electricity service through an interconnected system; however, several local solutions can be adopted, such as the use of diesel [44]. NIZ are shown in Figure 3. These locations have 130,000 population and contributes to 52% of Colombia's land, averagely 868 km^2 [44].

The department with the highest number of localities with ZNI is Nariño, followed by Chocó and Caquetá. Generally, the population density of the NIZ is extremely low (44 habitants/km2), due to the dispersion of both the municipalities and dwellings, a factor that makes the logistics of service assistance difficult, with high unit investment and operating costs [45]. This is due to the deficient, and in some places non-existent, mobility and transport infrastructure, aggravated by the political and socioeconomic conditions of the regions. Despite all, the NIZ are characterized by their great wealth of natural resources. Thanks to the abundance of resources, energy solutions should be based on renewable power sources as the hydraulic energy.

Figure 3. Non-interconnected zones. Adapted from: [46].

3.2. Electricity consumption in Colombia

The electricity consumption of a home is the sum of the electricity cost of all electrical appliances in the house in a given period (daily, weekly, monthly, annual, etc.). This is established using electrical energy measurement equipment, from which the electricity distributors extract the data for billing. Figure 4 shows the evolution of energy consumption per person.

Energy consumption includes electricity, cooking, transport, and heating. In Colombia, the average consumption per person is 10,000 kWh per year [28]. Between 1965 and 2021, the energy consumption had an increment of 120%; the average electricity consumption of a home depends directly on its dimensions, the number of people who live in it, appliances, and uses of electricity. Normally, the electrical appliances (oven, washing machine, television, refrigerator, computer, and air conditioning) are the same, and mostly, the electricity is consumed at night or on weekends. The average consumption of electricity in Colombia is still low compared to that is registered in the other economies of the region, as shown in Figure 4. This is the consequence of not having a "highly developed" electricity market and because gas, wood, and coal are still used as a source of energy, instead of electricity, in homes.

In the world, the countries with the highest energy consumption per person are Qatar (183,000 kWh per year), Netherlands Antilles (179,000 kWh per year) and Iceland (170,000 kWh per year). The consumption of United States of America ranks 18th with an average of 78,000 kWh per year. The world energy consumption per person is shown in Figure 5.

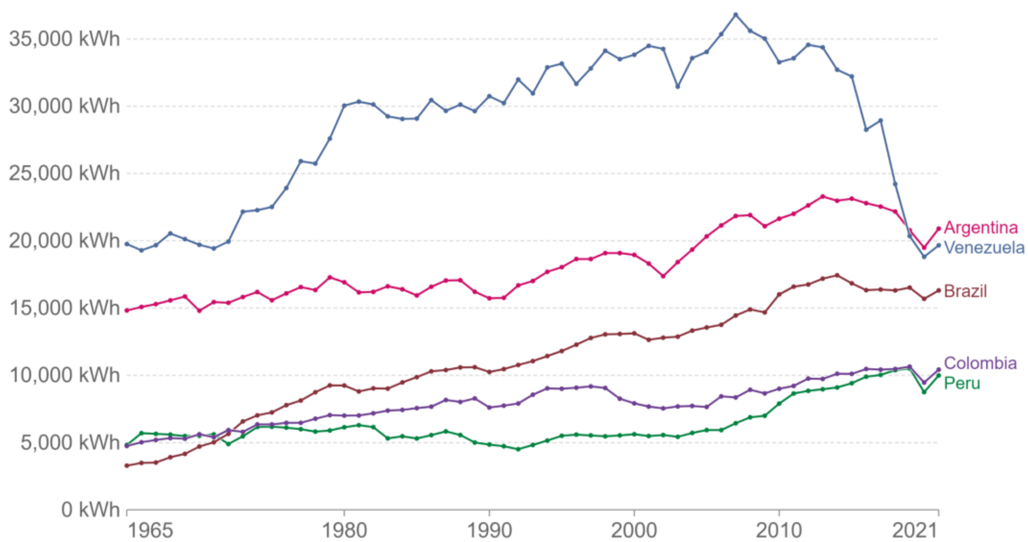

Figure 4. Energy use per person in Latin America [36].

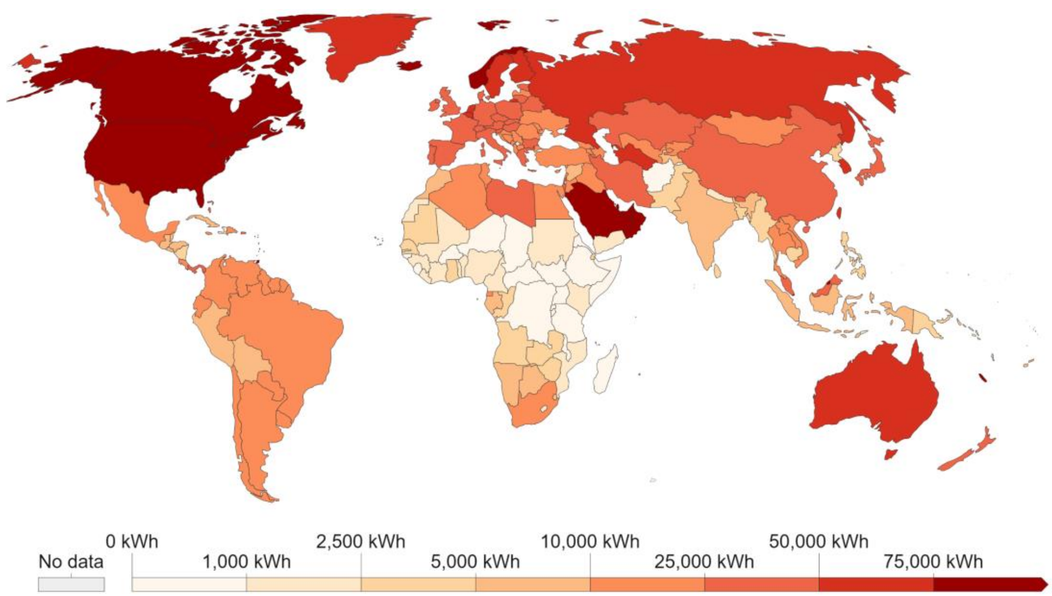

Figure 5. Energy use per person in the world [36].

4. Gravitational water vortex hydraulic turbine (GWVHT)

One of the new innovative turbines that take advantage of the potential energy resource for SHP is the GWVHT. GWVHT is an impulse turbine of low-head hydropower technology [47]. Low-head hydropower can generate electricity from rivers that were traditionally unsuitable for developing hydraulic power plants [42], [48]. In a GWVHT, the water passes through an inlet channel into a conical or cylindrical circulation chamber, in which a free surface water vortex is formed [49]. A vertical-axis runner is positioned in the center of the chamber. The runner rotates with the swirling flow, thus generating mechanical energy which can be converted to electrical energy using a generator [5]. The water discharges through an outlet hole at the bottom of the circulation chamber. A small hydroelectric plant with GWVHT is shown in Figure 6. The main components of this turbine are the inlet channel, circulation chamber or vortex chamber, and a runner or impeller.

The basic principle of any hydropower generation plant is impulse momentum [38]. Water potential is transformed into the mechanical energy by rotating a runner; next, mechanical energy is transformed into the electrical energy by using a generator. The diagram of converting the energy of water is shown in Figure 7.

The available power in an impulse turbine is given by Eq. 1:

$$P = \rho g Q(H_n) \qquad (1)$$

where ρ is the density of the fluid, Q the volume flow rate, g the gravity, and H is the difference in height between the level of fluid in the inlet channel and the position of the runner in the basin [51]. The power generated by any turbine is given by equation Eq. 2:

$$P_{out} = T\omega \qquad (2)$$

where T is the torque, and ω is the angular velocity. The efficiency η of the turbine is defined by equation Eq. 3:

$$\eta = \frac{P_{out}}{P} = \frac{T\omega}{\rho g Q(H_n)} \qquad (3)$$

Twenty of these turbines have been installed. The turbines installed have output powers ranging from 0.01 to 20 kW with an average efficiency of 54%± 12% [6]. This efficiency is low compared with the efficiencies reported by conventional turbine, with values that exceed 95% [52].

4.1. Prospects for the implementation of a GWVHT in Colombia

If Colombia has a potential of 25,000 MW for generation with SHP, for a power of 20 kW, about 1 million turbines could be installed. The potential for generation is higher than this installed capacity (19,000 MW). With a capacity of 20 kW, operating 18 h a day on average, and 350 days per year, each hydropower plant would supply the electricity for 13 million people. The NIZ only have 130,000 population.

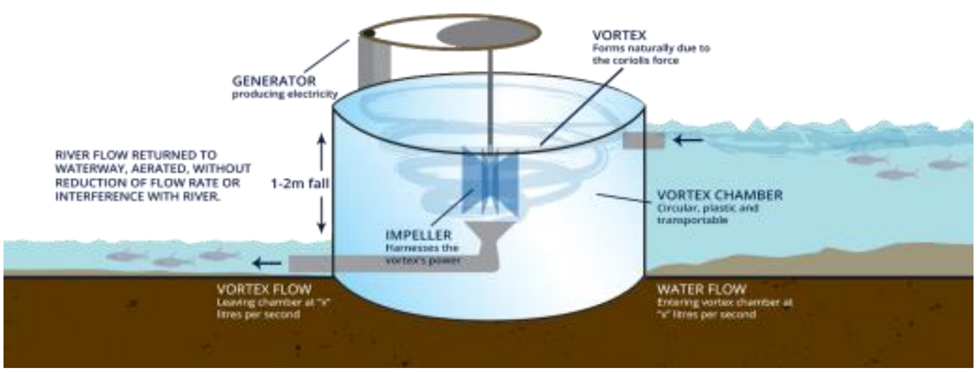

Figure 6. Small hydroelectric plant with GWVHT [50].

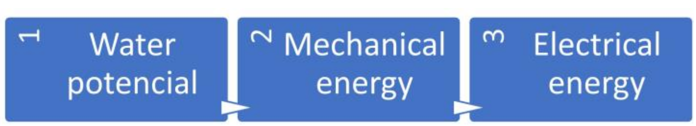

Figure 7. Block diagram of hydropower generation. Adapted from: [38].

Producing electricity taking advantage of the potential available in the country not only makes it possible to supply the energy needs of the NIZ, but it would also allow generating electricity for the rest of the country, including neighboring countries. An interesting proposal to produce electricity for noninterconnected zones, or to deal with the growing demand for electricity, is to use the water discharges available in large-hydroelectric plants. Water discharges are the amount of water expressed in energy [GWh] that is evacuated from the reservoirs (damns) through their discharge structures. This occurs in the rainy seasons when the reservoir level exceeds its maximum physical level. The spillway is a hydraulic structure built to allow free passage or control the water stored in a reservoir. There are different types of discharge structures.

In Colombia, the most used types of landfills are those with the free edge, landfills with gates and landfills with fuse dams [53]. In a free - edge weir, the water passes freely over them once the reservoir exceeds the level of said structure. Weirs with gates are those that can control the discharge by partially or totally opening their gates.

These spillways do not have to wait for the reservoir to reach its maximum operating level to start opening their gates; the operation begins in advance seeking to regulate the discharge of the flow and maintain the level of the reservoir. A fusible dam spillway is made up of independent units that collapse when the water level in the reservoir reaches a certain level, causing the flow to discharge downstream through the space released by this unit.

Figure 8 shows the water discharge that is evacuated from the reservoirs for all hydropower plants in Colombia in the last two years. In total, in the last 2 years, 12,612 GWh of energy has been wasted through discharge structures.

Figure 9 shows the evolution of the average daily price of electricity from 2016 to 2020. Table 1 shows the Average Market Exchange Rate between 2016 and 2022.

Table 1. Average Market Exchange Rate

Year	Average Market Exchange Rate
2016	1 USD = 3,050.98 COP
2017	1 USD = 2,984.00 COP
2018	1 USD = 2,956.55 COP
2019	1 USD = 3,281.09 COP
2020	1 USD = 3,693.36 COP
2021	1 USD = 3,743.09 COP
2022	1 USD = 4,255.44 COP

Banco de la República, Colombia.

In Colombia, the highest percentage of generation is covered by generators with hydroelectric plants. When the weather affects the level of the reservoir downwards, it puts pressure on the price, and this effect is noticeable.

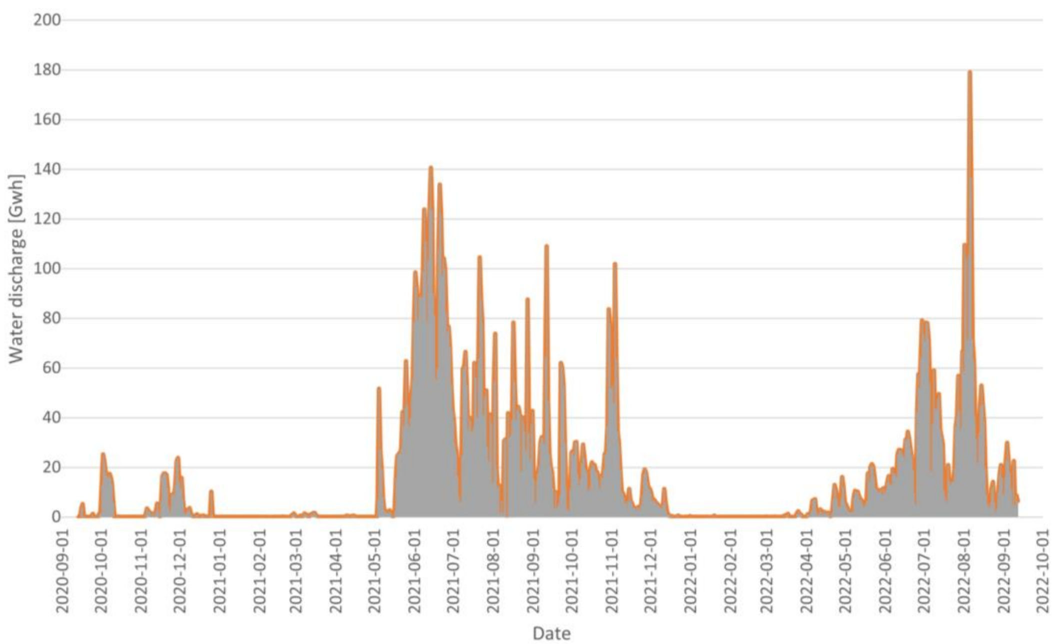

Figure 8. Water discharge. Adapted from: [53].

According to Figure 9, in the first months of 2016 with the formation of the El Niño phenomenon that affected the country between 2015 and 2016, when the price reached 871 COP (0.285 USD Average Market Exchange Rate for 2016). Throughout 2019 and 2020, the effects of climate change and the influence of the El Niño phenomenon are observed too. With an average cost of 200 COP (0.055 USD Average Market Exchange Rate for 2020) per kWh, the water discharged in the last two years (12,612 GWh) was equivalent to 2,522,400.000 COP (682,955.35 USD).

In the NIZ, the cost of electricity (generated with fossil fuels) is on average 1,250 COP (0.338 USD) per kWh [54], so the value of water discharges would be equivalent to 15,765,000,000 COP (4,268,470.98 USD). In the ZNI, the cost of electricity increases due to the transport of fossil fuel added to the difficulty of access.

A barrel of oil is equal to 6.1178632 x 10^9 or 1,700 kWh [56]. water discharge is equivalent to 7,400 barrels of oil. Figure 10 shows the evolution of the price of OPEC oil. OPEC oil has been quoted during 2022 at an average of 94 USD per barrel [57]. OPEC is the Organization of Petroleum Exporting Countries, coordinates the oil policies of its member countries to influence the international oil market. OPEC member countries are the United Arab Emirates, Saudi Arabia, Algeria, Venezuela, Nigeria, Angola, Qatar, Ecuador, Libya, Gabon, Iran, Iraq, and Kuwait [58]. The 7,400 barrels will cost 695,600 USD (or approximately 2,960,084 COP Average Market Exchange Rate for 2022).

5. Barriers and opportunities in Colombian hydropower development

The future of humanity depends on the way energy is produced [60].

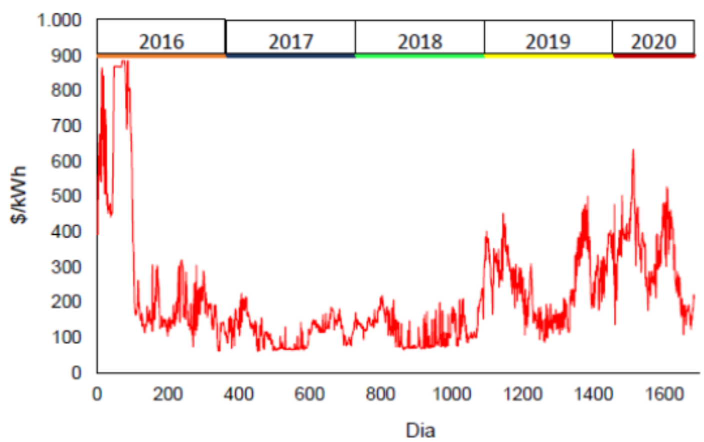

Figure 9. The evolution of the average daily price of electricity [55].

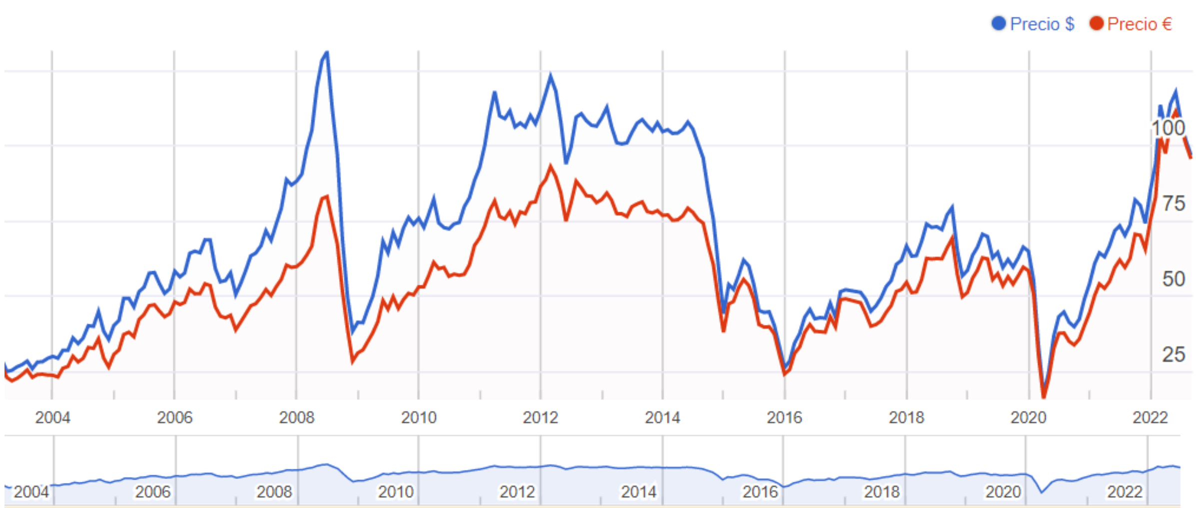

Figure 10. Evolution of the price of OPEC oil [59].

Currently, most countries worldwide aim to supply their internal energy demand from renewable energy sources [61]. Colombia is not a stranger to this approach, as in the National Energy Plan, a strategy to reduce the vulnerability of the energy sector is the search to diversify the matrix of electricity generation in the medium and long term in all supply chains energy supply, increasing its complementarity, availability, and reliability with renewable energy sources [62]. In this regard, developing countries are facing the following challenges: i) development and technological adaptation of devices for the use from renewable energy sources; ii) the formation of human capital in aspects related to energy generation and energy efficiency; and iii) the search for sources of investment for developing the energy infrastructure necessary to continue guaranteeing equity and social development, while simultaneously addressing the effects of climate change and sustainable development. From renewable energy sources, hydropower is considered as one of the most convenient and popular renewable energy technologies [63], [61], [64].

- Environmental sustainability and land use: During the construction period of a hydropower plant, land is busy to make temporal activities like construction of roads, stores, and worksites [61], [65]. The temporal land occupied for constructing may include urban, forests and farmlands. After the conclusion of the construction period, large areas of land are permanently flooded. Large storage of water in big artificial lake causes biomass decomposition of flooded land and produces methane (CH_4) and carbon dioxide (CO_2) emissions. Additionally, floodedland destroys arable land, wildlife, and can included residential areas. Reservoirs in hilly regions can store more water in smaller areas, whereas in flat regions the area covered by the reservoir is large [61]. For instance, the hydroelectric power plant located in "El Peñol" dam (Guatapé, Antioquia) floods 74 km^2 of land to generate 560 MW [66]. The Three Gorges Dam, the world's largest hydropower plant, floods 1,084 km^2 of land to generate 22,500 MW [67], [68]. Small-hydropower plants, especially run of river type schemes, do not have the same environmental problems associated with large hydroelectric projects since these types of plants do not require large reservoirs [69], even some of them, such as gravitational water vortex hydraulic turbine, do not require any type of reservoir. As in any turbine, GWVHT can produce downstream flow alterations; nevertheless, in the case of GWVHT, these alterations can be advantageous because they allow aerating the water, disseminating internal pollutants in the water, and reducing the temperature by increasing the rate of evaporation [70], [6], [4].

- Government policies: In the New Policies Scenario, the world meets its growing energy needs in a radically different way than in the last 25 years, now led by natural gas, the rapid rise of renewable energies, and energy efficiency [42]. The decisions agreed at United Nations Climate Change Conference 2015 (COP21) light up the future of renewable energies. The international community has understood its debt to strengthen the transition to a low-carbon economy for the sustainable future. The unanimity in favor of the decarbonization of the economy constitutes a very favorable framework for the promotion of clean energy technologies. As large hydropower projects are not accepted as a clean renewable energy source by environmentalists and ecologists, many countries accelerated the growth of SHP [71], [72]. To promote the expansion of SHP, the governments have financed investigations and developments of technologies to make such power plant a competitive one, establishing regulatory frameworks and policies to the renewable energy sector [73]. In the case of Colombia, Law 1715 of 2014 marked a milestone in the country's energy history, encouraging the use of non-conventional sources of energy, turning them into a matter of public utility and social, public, and national interest, which triggered a high interest in the promotion and implementation of energy projects through nonconventional sources of energy in the country [74], [75].

6. Conclusions

In Colombia, the electricity sector is one of the most competitive in the region and thanks to its good management, it is one of the sectors with the highest profits and projection. More than 52% of the territory does not have a constant electricity service at reasonable prices, which prevents the development of these areas, increasing the inequality that already affects Colombian society, especially at the regional level. Access in rural areas and particularly in NIZ is very poor and, although coverage has been expanded in recent years, quality has not been increased to the same extent.

Therefore, it is important that electrification projects not only provide electricity to inhabitants, but also temporary and permanent jobs allowing community development and the inclusion of the various local actors that lead local development, and the project to be carried out. For this purpose, a fundamental and integral role of the state that allows reducing the technological, social and economic gap is required, in which people without electricity can live, respecting and rescuing their worldviews, cultures and social constructions. Due to the present restrictions to lead to the interconnection of the NIZ to the SIN, it is important to pay special attention and allocation to research and development in alternative energies that enable access to electricity at reasonable costs and without having permanent impacts on the environment.

In this regard, public and private interventions are necessary in the electricity service providers in the NIZ to make attractive and safe investments in the sector. Likewise, understanding the role played by the glider when seeking reasonable and applicable solutions in each of the NIZ is a complex task, due not only to the growing supply of new alternatives, but also to the complexity of the Colombian territory that sometimes makes the application of such technologies difficult.

GWVHT are a promising technology because they allow to take advantage of locations that until now were impossible with conventional generation systems (Pelton, Kaplan, and Francis turbine) since this technology requires a low hydraulic head.

Funding

We acknowledge the financial support provided by the announcement No. 890 de 2020 “Convocatoria para el fortalecimiento de CTeI en Instituciones de Educación Superior (IES) Públicas 2020” (Contract No. 2022-0453). Additionally, authors acknowledge the financial support provided by Universidad de Antioquia (Estrategia de Sostenibilidad 2020-2021 ES84190067).

Autor Contributions

L. Velásquez: Investigation, Conceptualization, Investigation, Methodology, Writing – original draft. A. Rubio-Clemente: Methodology, Writing – review & editing. A. Posada: Writing – review & editing. E. Chica: Conceptualization, Supervision, Writing - review & editing.

All authors have read an agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

References

[1] E. F. Moran, *People and nature: An introduction to human ecological relations*. John Wiley & Sons, 2016.

[2] T. Van de Graaf, B. K. Sovacool, *Global energy politics*. John Wiley & Sons, 2020.

[3] I. Stoddard et al., “Three Decades of Climate Mitigation: Why Haven’t We Bent the Global Emissions Curve,” *Annu. Rev. Environ. Resour*., vol. 46, no. 1, pp. 653–689, Oct. 2021, doi: https://doi.org/10.1146/annurev-environ-012220-011104

[4] L. Velásquez, E. Chica, J. Posada-Montoya, “Advances in the Development of Gravitational Water Vortex Hydraulic Turbines,” *J. Eng. Sci. Technol. Rev*., vol. 14, pp. 1–14, 2021, doi: https://doi.org/10.25103/jestr.143.01

[5] A. Tesfaye, V. Ancha, G. Tibba, “Numerical analysis of the effect of runner-to-basin diameter ratio on the performance of gravitational water vortex turbine in a scroll basin,” *Int. J. Energy Environ. Eng.*, vol. 13, pp. 1317–1333, 2022, doi: https://doi.org/10.1007/s40095-022-00495-4

[6] A. B. Timilsina, S. Mulligan, T. R. Bajracharya, “Water vortex hydropower technology: a state-of-the-art review of developmental trends,” *Clean Technol. Environ. Policy*, vol. 20, pp. 1737–1760, 2018.

[7] V. J. Alzamora Guzmán, J. A. Glasscock, “Analytical solution for a strong free-surface water vortex describing flow in a full-scale gravitational vortex hydropower system,” *Water Sci. Eng*., vol. 14, no. 1, pp. 72–79, Mar. 2021, doi: https://doi.org/10.1016/j.wse.2021.03.004

[8] J. A. Aguilera Folgueiras, “Fuentes de energía y Protocolo de Kioto en la evolución del sistema eléctrico español,” Jul. 2012. [Online]. Available: http://hdl.handle.net/10651/13052

[9] J. A. J. Gowlett, “The discovery of fire by humans: a long and convoluted process,” *Philos. Trans. R. Soc. B Biol. Sci.*, vol. 371, no. 1696, p. 20150164, 2016, doi: https://doi.org/10.1098/rstb.2015.0164

[10] G. A. Tokaty, *A History and Philosophy of Fluid Mechanics*. Dover, 1994. [Online]. Available: https://books.google.com.co/books?id=ZmgJDgkDx8UC

[11] R. L. Hills, *Power from Wind: A History of Windmill Technology*. Cambridge University Press, 1996. [Online]. Available: https://books.google.com.co/books?id=FoVkfkBV1%5C_8C

[12] J. LANGDON, "Water-mills and windmills in the west midlands, 1086-1500," *Econ. Hist. Rev.*, vol. 44, no. 3, pp. 424–444, 1991, doi: https://doi.org/10.1111/j.1468-0289.1991.tb01272.x

[13] A. Vázquez Pérez, M. Rodriguez Gamez, C. Gustavo, V. Viteri, A. Vélez Quiroz, "Community Power as a Driving Force for Sustainable Local Development," *Int. Res. J. Eng. IT Sci. Res.*, vol. 3, pp. 7–17, 2017.

[14] G. Parker, Global Crisis: War, *Climate Change, & Catastrophe in the Seventeenth Century*. Yale University Press, 2013. [Online]. Available: https://books.google.com.co/books?id=gjdDP15N4FkC

[15] S. Liu et al., "Coal-fuelled crucible lead-silver smelting in 12th-13th century China: A technological innovation in the age of deforestation," *J. Archaeol. Sci.*, vol. 104, pp. 75–84, 2019, doi: https://doi.org/10.1016/j.jas.2019.01.004

[16] J. Dodson et al., "Use of coal in the Bronze Age in China," *The Holocene*, vol. 24, pp. 525–530, 2014, doi: https://doi.org/10.1177/0959683614523155

[17] H. W. Dickinson, *A Short History of the Steam Engine*. Cambridge University Press, 2011. [Online]. Available: https://books.google.com.co/books?id=8yug4QCWwywC

[18] J. A. Montagna, "*The Industrial Revolution," Curric*. Units, vol. 2, 1981.

[19] M. Piccolino, "The bicentennial of the Voltaic battery (1800–2000): the artificial electric organ," *Trends Neurosci.*, vol. 23, no. 4, pp. 147–151, Apr. 2000, doi: https://doi.org/10.1016/S0166-2236(99)01544-1

[20] E. R. Laithwaite, "The influence of Michael Faraday on power engineering," *Power Eng. J.*, vol. 5, no. 5, p. 209, 1991, doi: https://doi.org/10.1049/pe:19910043

[21] G. Adair, *Thomas Alva Edison: Inventing the Electric Age*. Oxford University Press, USA, 1996. [Online]. Available: https://books.google.com.co/books?id=hEffwEC7hGsC

[22] J. Lienhard, "A Century of Innovation: Twenty Engineering Achievements that Transformed Our Lives A Century of Innovation: Twenty Engineering Achievements that Transformed Our Lives, George Constable and Bob Somerville Joseph Henry Press, Washington, DC, 2003. $45.00," *Phys. Today*, vol. 57, no. 12, pp. 63–63, 2004, doi: https://doi.org/10.1063/1.1878337

[23] S. Rațiu, "The history of the internal combustion engine," *Ann. Fac. Eng. Hunedoara*, vol. 1, pp. 145–148, 2003.

[24] J. J. Flink, *The Automobile Age*. MIT Press, 1990. [Online]. Available: https://books.google.com.co/books?id=7WtKH-9ha4MC

[25] N. Armaroli, V. Balzani, *Energy for a Sustainable World*. Wiley, 2010. doi: https://doi.org/10.1002/9783527633593

[26] J. Mohtasham, "Review Article-Renewable Energies," *Energy Procedia*, vol. 74, pp. 1289–1297, Aug. 2015, doi: https://doi.org/10.1016/j.egypro.2015.07.774

[27] M. Taylor, et al, "Energy subsidies: Evolution in the global energy transformation to 2050".

[28] T. Ahmad, D. Zhang, "A critical review of comparative global historical energy consumption and future demand: The story told so far," *Energy Reports*, vol. 6, pp. 1973–1991, 2020, doi: https://doi.org/10.1016/j.egyr.2020.07.020

[29] British Petroleum, "Bp full report–statistical review of world energy 2021." 2021. [Online]. Available: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf

[30] S. Arango-Aramburo, J. P. Ríos-Ocampo, E. R. Larsen, "Examining the decreasing share of renewable energy amid growing thermal capacity: The case of South America," *Renew. Sustain. Energy Rev.*, vol. 119, p. 109648, 2020, doi: https://doi.org/10.1016/j.rser.2019.109648

[31] S. Carrizo and S. Velut, "Energy transitions and regional integration in South America," *in Territorial planning and La Plata Basin borders, Editora Letra1*, 2018, pp. 167–187. doi: https://doi.org/10.21826/9788563800350-06

[32] S. Zapata, M. Castañeda, A. Aristizábal, I. Dyner, "Renewables for supporting supply adequacy in Colombia," *Energy*, vol. 239, p. 122157, 2021, doi: https://doi.org/10.1016/j.energy.2021.122157

[33] A. Cáceres, P. Jaramillo, H. Matthews, C. Samaras, B. Nijssen, "Hydropower under climate uncertainty: Characterizing the usable capacity of Brazilian, Colombian and Peruvian power plants under climate scenarios," *Energy Sustain. Dev*., vol. 61, pp. 217–229, 2021, doi: https://doi.org/10.1016/j.esd.2021.02.006

[34] T. Santos, "Regional energy security goes South: Examining energy integration in South America," *Energy Res. Soc. Sci*., vol. 76, p. 102050, 2021, doi: https://doi.org/10.1016/j.erss.2021.102050

[35] S. N. Abdul Latif et al., "The Trend and Status of Energy Resources and Greenhouse Gas Emissions in the Malaysia Power Generation Mix," *Energies*, vol. 14, no. 8, p. 2200, 2021, doi: https://doi.org/10.3390/en14082200

[36] Hannah Ritchie and Pablo Rosado, "Energy: Key Charts," 2021. https://ourworldindata.org/energy-key-charts

[37] O. A. C. Hoes, L. J. J. Meijer, R. J. van der Ent, N. C. van de Giesen, "Systematic high-resolution assessment of global hydropower potential," *PLoS One*, vol. 12, no. 2, p. e0171844, 2017, doi: https://doi.org/10.1371/journal.pone.0171844

[38] V. K. Singh, S. K. Singal, "Operation of hydro power plants-a review," *Renew. Sustain. Energy Rev*., vol. 69, pp. 610–619, 2017, doi: https://doi.org/10.1016/j.rser.2016.11.169

[39] T. S. Kishore, E. R. Patro, V. S. K. V. Harish, A. T. Haghighi, "A Comprehensive Study on the Recent Progress and Trends in Development of Small Hydropower Projects," *Energies*, vol. 14, no. 10, p. 2882, May 2021, doi: https://doi.org/10.3390/en14102882

[40] J. Górecki, E. Płoszaj, "Cost risk of construction of small hydroelectric power plants," *MATEC Web Conf*., vol. 262, p. 07004, 2019, doi: https://doi.org/10.1051/matecconf/201926207004

[41] H. Jangavar, Y. Noorollahi, A. Emami Meybodi, "Economic and Environmental Analysis of the Small Hydropower Plants Development," *Iran. J. Ecohydrol*., vol. 4, no. 4, pp. 1255–1268, 2017, doi: https://doi.org/10.22059/ije.2017.63271

[42] J. Chen, A. Engeda, "Standard Module Hydraulic Technology: A Novel Geometrical Design Methodology and Analysis for A Low-Head Hydraulic Turbine System, Part I: General design methodology and basic geometry considerations.," *Energy*, vol. 196, p. 117151, 2020, doi: https://doi.org/10.1016/j.energy.2020.117151

[43] S. M. Puentes, A. H. Q. Duque, "Formulación de estrategias para la implementación y fomento de fuentes no convencionales de energías renovables en zonas no interconectadas de Colombia," 2021.

[44] S. de S. P. Domiciliarios, "Zonas no interconectadas ZNI, diagnóstico de la prestación del servicio de energía eléctrica 2017," p. 43, 2017.

[45] S. de S. P. Domiciliarios, "Zonas no interconectadas– ZNI informe sectorial de la prestación del servicio de energía eléctrica 2021," p. 41, 2021.

[46] J. Carlos Rojas, "El mapa de 1.710 poblados que aún se alumbran con velas en Colombia," El tiempo, 2019. [Online]. Available: https://www.eltiempo.com/colombia/otras-ciudades/los-poblados-que-aun-no-tienen-energia-electrica-en-colombia-324980

[47] V. Guzmán, J. Glasscock, F. Whitehouse, "Design and construction of an off-grid gravitational vortex hydropower plant: A case study in rural Peru," *Sustain. Energy Technol.*, vol. 35, pp. 131–138, 2019, doi: https://doi.org/10.1016/j.seta.2019.06.004

[48] D. S. Edirisinghe, H. S. Yang, S. D. G. S. P. Gunawardane, Y. H. Lee, "Enhancing the performance of gravitational water vortex turbine by flow simulation analysis," *Renew. Energy*, vol. 194, pp. 163–180, 2022, doi: https://doi.org/10.1016/j.renene.2022.05.053

[49] L. Velásquez, A. Posada, E. Chica, "Optimization of the basin and inlet channel of a gravitational water vortex hydraulic turbine using the response surface methodology," *Renew. Energy*, vol. 187, pp. 508–521, 2022, doi: https://doi.org/10.1016/j.renene.2022.01.113

[50] Kourispower, "Waterway embodiment of KCT," 2021. https://www.kourispower.com/technology/

[51] I. Adejumobi, D. Shobayo, "Optimal Selection of Hydraulic Turbines for Small Hydro Electric Power Generation – A Case Study of Opeki River, South Western Nigeria," *Niger. J. Technol*., vol. 34, p. 530, 2015, doi: https://doi.org/10.4314/njt.v34i3.15

[52] D. Y. Goswami, F. Kreith, Eds., *Energy Conversion. CRC Press*. 2007, doi: https://doi.org/10.1201/9781420044324

[53] XM, "Vertimientos." https://www.xm.com.co/hidrología/vertimientos

[54] Grupo de Investigación Xué, S. D. I. Barión, "Estado de la cobertura eléctrica y las zonas no interconectadas en la región central," 2020.

[55] M. Gamboa, F. F. Serrano, E. G. Gómez, Gustavo, "*Mercados de energía en Colombia, una introducción al área*.," Sello Editor. Univ. Pamplona, 2021, [Online]. Available: http://repositoriodspace.unipamplona.edu.co/jspui/handle/20.500.12744/2827

[56] E. L. Gonzales Titi, P. A. Loayza Quiñones, A. M. More Dávila, V. A. R. Simeon Vega, "Propuesta de utilización del gas natural licuefactado en los camiones mineros: evaluación de beneficios," 2019. [Online]. Available: https://hdl.handle.net/20.500.12640/1737

[57] H. Duan, Y. Liu, G. Wang, "A novel dynamic time-delay grey model of energy prices and its application in crude oil price forecasting," *Energy*, vol. 251, p. 123968, 2022, doi: https://doi.org/10.1016/j.energy.2022.123968

[58] Ò. Bosede Comfort, H. Okodua, M. Oladosun, A. Asaleye, "Human capital and poverty reduction in OPEC member-countries," *Heliyon*, vol. 5, p. e02279, 2019, doi: https://doi.org/10.1016/j.heliyon.2019.e02279

[59] Expansion, "Precio del petróleo opep por barril," 2022. https://datosmacro.expansion.com/materias-primas/opec?anio=2022

[60] C. Zou et al., "The role of new energy in carbon neutral," *Pet. Explor. Dev*., vol. 48, no. 2, pp. 480–491, 2021, doi: https://doi.org/10.1016/S1876-3804(21)60039-3

[61] H. Nautiyal, V. Goel, "Sustainability assessment of hydropower projects," *J. Clean. Prod*., vol. 265, p. 121661, 2020, doi: https://doi.org/10.1016/j.jclepro.2020.121661

[62] UPME, "Plan energético nacional Colombia: ideario energético 2050," 2015.

[63] M. Kumar, "Social, Economic, and Environmental Impacts of Renewable Energy Resources," in *Wind Solar Hybrid Renewable Energy System*, *IntechOpen*, 2020. doi: https://doi.org/10.5772/intechopen.89494

[64] M. Abdel-Basset, A. Gamal, R. K. Chakrabortty, M. J. Ryan, "Evaluation approach for sustainable renewable energy systems under uncertain environment: A case study," *Renew. Energy*, vol. 168, pp. 1073–1095, 2021, doi: https://doi.org/10.1016/j.renene.2020.12.124

[65] C. Li et al., "Evaluating the impact of highway construction projects on landscape ecological risks in high altitude plateaus," *Sci. Rep*., vol. 12, no. 1, p. 5170, 2022, doi: https://doi.org/10.1038/s41598-022-08788-8

[66] J. A. Vélez Henao, et al., "Evaluación de las transferencias del sector eléctrico. El caso de San Carlos y el Oriente Antioqueño," *Rev. Ing. Univ. Medellín*, vol. 14, pp. 147–161, 2015.

[67] Y. Lu, C. Shang, "The environmental impact of the three gorges project and the countermeasures," *Front. Eng. Manag*., pp. 120–128, 2014.

[68] H. Zhenli, B. Wu, *Three Gorges Dam: Environmental Monitoring Network and Practice*, 2018, pp. 1–14. doi: https://doi.org/10.1007/978-3-662-55302-2_1

[69] A. Kumar, Z.G. Yu, J. J. Klemeš, A. Bokhari, "A state-of-the-art review of greenhouse gas emissions from Indian hydropower reservoirs," *J. Clean. Prod*., vol. 320, p. 128806, 2021, doi: https://doi.org/10.1016/j.jclepro.2021.128806

[70] M. M. Rahman, J. H. Tan, M. T. Fadzlita, A. R. Wan Khairul Muzammil, "A Review on the Development of Gravitational Water Vortex Power Plant as Alternative Renewable Energy Resources," *IOP Conf. Ser. Mater. Sci. Eng*., vol. 217, p. 012007, 2017.

[71] T. Couto, J. Olden, "Global proliferation of small hydropower plants - science and policy," *Front. Ecol. Environ*., vol. 16, 2018, doi: https://doi.org/10.1002/fee.1746

[72] T. Abbasi, S. A. Abbasi, "Small hydro and the environmental implications of its extensive utilization," *Renew. Sustain. Energy Rev*., vol. 15, no. 4, pp. 2134–2143, 2011, doi: https://doi.org/10.1016/j.rser.2010.11.050

[73] E. Renovables and D. Irena, "10 argumentos a favor de las energías renovables," 2015.

[74] A. Gómez, C. Arredondo, M. Luna, S. Villegas, J. Hernandez, "Regulating the integration of renewable energy in Colombia: Implications of law 1715 of 2014," *IEEE 44th Photovoltaic Specialist Conference (PVSC)*, 2017, doi: https://doi.org/10.1109/PVSC.2017.8366780

[75] J. A. Hernandez, C. A. Arredondo, D. J. Rodriguez, "Analysis of the law for the integration of non-conventional renewable energy sources (law 1715 of 2014) and its complementary decrees in Colombia," *in 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC)*, 2019, pp. 1695–1700, doi: https://doi.org/10.1109/PVSC40753.2019.8981233