Evaluation of Innovative Technologies for Small-Scale Hydroelectric Systems: Future Perspectives

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ABSTRACT
The document analyzes emerging technologies for small-scale hydroelectric systems in Ecuador, focusing on their application in rural areas with limited access to electrical grids. The research explores the use of low-flow turbines and hybrid solutions, combining solar and hydraulic energy to optimize the efficiency and sustainability of these systems. The methodology includes expert interviews and field data collection in the Tungurahua province, evaluating key aspects such as technological efficiency, costs, environmental impact, and community acceptance. Regarding the results, several turbines were evaluated, including the Pelton, Francis, Kaplan, and Turgo models, each adapted to specific characteristics of flow and head height in different rivers. The analyzes show that the Pelton turbine is highly efficient in moderate flows and steep gradients, while the Kaplan turbine adapts better to variable flows, increasing stability in fluctuating flow environments. Pumped storage and battery systems complement these technologies by stabilizing energy supply. Additional benefits highlighted by the results include job creation and local infrastructure improvements, which strengthen the community economy. However, technical challenges remain, such as a lack of spare parts and logistical difficulties in mountainous areas. In conclusion, the study recommends strengthening supply chains and improving technical training to overcome these challenges, positioning small-scale hydroelectric systems as a sustainable and viable option for energy development in Ecuador, aligned with the goals of energy transition and sustainable rural development.

Keywords: evaluation, technology, systems, scale.

INTRODUCTION

Ecuador, with its extensive hydrographic network covering more than 50% of the territory, offers significant potential for the development of small-scale hydroelectric systems. However, these projects face unique challenges, such as variability in flow rates and the complex topography of the Andean regions. Despite this, the implementation of these technologies would not only contribute to the diversification of the energy matrix, but would also boost economic development in rural areas, aligning with the UN Sustainable Development Goals (SDGs).

Hydroelectric projects in countries such as Colombia and Peru have shown positive results in the implementation of small-scale technologies for rural areas, with direct impacts on job creation and infrastructure improvement. Similarly, in Ecuador, emerging technologies such as Kaplan and Pelton turbines have shown great potential not only in terms of energy efficiency, but also in strengthening local economies by generating employment and development opportunities in the most remote rural areas (Rojas Asuero, Duque Yaguache & García Ramírez, n.d.).

The growing global demand for electric energy, coupled with environmental concerns arising from climate change and the need to diversify energy matrices and sources, has driven the search for more efficient and sustainable renewable energy sources; seeking alternatives with low environmental impact, mainly in remote areas and populations without access to traditional networks. Among these, hydroelectric energy, particularly in its small-scale form, is presented as an attractive alternative due to its capacity to generate electricity in a clean and reliable manner (Pinto & Rodríguez, 2021).

According to Torrego and Martínez-Frias (nd), the national territory is divided into 31 hydrographic systems, which comprise 79 basins. Of these, 24 basins drain from the Andes to the Pacific Ocean, covering an area of 123,243 km^2, representing 48.07% of the national territory. On the other hand, 7 basins flow towards the Eastern Region, covering an area of 131,802 km^2, equivalent to 51.41% of the national territory. The island surface close to the continent is 1,325 km^2, representing 0.52% of the national territory. The annual water contributions of the national hydrographic network, with a probable margin of error of 30%, are 110 billion m^3 on the Pacific Ocean slope and 290 billion m^3 on the Amazon slope. There is a notable heterogeneity in the spatial distribution of flows across the different geographic regions of Ecuador, due to the varied physical-climatic conditions that predominate in the country. The use of groundwater is generally low, except in the Latacunga basin.

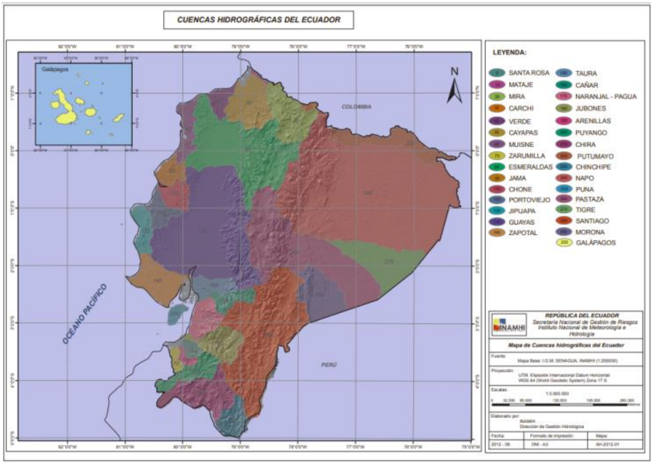


Figure 1. Hydrographic Basins of Ecuador
Note: National Institute of Meteorology and Hydrology. (2012).

Historically, INECEL and several electric companies dominated production and marketing, but the Modernization Law has allowed for greater private sector participation following the dissolution of INECEL. Regulation and control of the electricity sector in Ecuador is under the responsibility of CONELEC, while CENACE manages transactions in the wholesale electricity market. Although electricity coverage is high in both urban and rural areas, hydroelectric projects face significant challenges in water resource management. Sedimentation in reservoirs directly affects their storage capacity and reduces their useful life, while equipment wear is a consequence of sediment accumulation. To mitigate these problems, projects such as the Mazar Hydroelectric Power Plant have been implemented, as well as integrated watershed management programs on key rivers such as the Paute and Pastaza, which seek to reduce sediment load and improve the operational efficiency of hydroelectric plants (Rojas Asuero, Duque Yaguache & García Ramírez, n.d.).

In 2008, approximately 46% of energy in Ecuador came from fossil sources, while hydroelectric energy accounted for 43% of energy production. By 2016, the share of hydroelectric energy increased to 58.08% of effective generation capacity. By 2024, this percentage increased to around 64%, reflecting the country's sustained effort to diversify its energy matrix and reduce dependence on fossil fuels (Ministry of Energy and Mines of Ecuador, 2024). However, the sector faces a new challenge: the marked scarcity of rainfall in several regions, a situation exacerbated by climate change, which has affected river flows and the availability of water for hydroelectric plants. This reality has highlighted the vulnerability of the Ecuadorian energy matrix to climate variability and highlights the need to strengthen strategies for energy diversification and integration of alternative renewable sources.

The development of mini hydroelectric plants in Ecuador not only responds to the need to increase the country's electricity generation capacity, but also aligns with the UN Sustainable Development Goals (SDGs). Projects such as HYPOSO (Hydropower Solutions for Developing and Emerging Countries), funded by the European Union's Horizon 2020 programme, demonstrate the international commitment to the development of hydroelectric solutions adapted to the local needs of developing countries (Haro et al.).

According to Haro, in his document: Ecuador, target country of the HYPOSO project "Hydropower Solutions for Emerging Countries" highlights that the implementation of small hydroelectric plants can play a crucial role in the supply of energy in rural and isolated areas, where the expansion of traditional electricity networks is economically unviable. The mini-plants, with capacities that generally vary between 1 and 10 MW, offer a flexible solution adapted to local conditions. Among the highlighted projects in Ecuador are Palmira - Nanegal, Tandayapa and Gala, which have been designed at the pre-feasibility level as part of the HYPOSO project (Hydropower Solutions for Developing and Emerging Countries). These projects exemplify how small-scale hydroelectric technologies can be integrated into national energy strategies to improve access to electricity and promote sustainable development (Haro).

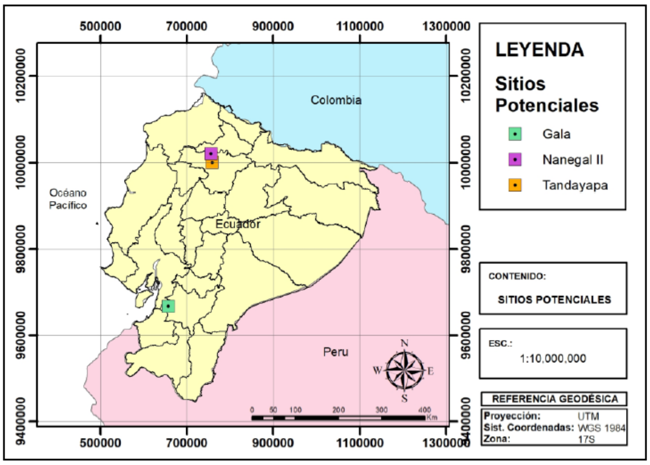


Figure 2. Geographic location of the Palmira - Nanegal, Tandayaca and Gala projects.

This paper aims to analyse and evaluate emerging technologies and innovative practices applied in small-scale hydroelectric systems, focusing on the electrical potential of systems such as those developed in Palmira - Nanegal, Tandayapa and Gala. Through the analysis of these and other case studies in various regions, the aim is to identify best practices and technologies that can be replicated or adapted in similar contexts. It also addresses the technical barriers that limit the expansion of these technologies, as well as the opportunities they offer for sustainable development and energy transition in countries with high untapped hydroelectric potential.

Small-scale hydroelectric systems have undergone significant evolution in recent decades, thanks to technological advances, optimization of hydraulic designs, and increasing sophistication of control systems. However, the sector still faces challenges related to efficiency, sustainability, adaptability to changing environmental conditions, and integration into increasingly complex power grids (Pinto & Rodríguez, 2021).

Finally, it is recommended how the implementation of these innovative technologies can contribute to improving the resilience of local communities in the face of energy and environmental challenges, ensuring a reliable and sustainable energy supply for the Ambato canton. In a world increasingly oriented towards sustainability, the role of mini hydroelectric plants becomes important, not only to diversify the energy matrix, but also to promote equity and development in rural and neglected areas.

MATERIALS AND METHODS

The technologies analyzed in this study were selected based on their relevance to small-scale environments, particularly those that have proven to be efficient in areas with limited water resources. Qualitative data collection was conducted through interviews with 15 hydroelectric and renewable energy experts in Ecuador, using a series of structured questions to identify the main barriers and opportunities in the implementation of these technologies.

The research comprises two phases: Qualitative and Quantitative. In the qualitative phase, a literature review was conducted focusing on small-scale hydroelectric technologies in Ecuador, analyzing emblematic projects such as Palmira - Nanegal, Tandayapa and Gala, and in-depth interviews were conducted with experts in hydraulic engineering and renewable energy to identify trends and challenges specific to the Ecuadorian context. In the quantitative phase, structured surveys were designed to evaluate the efficiency and viability of these technologies, applied to users and operators of hydroelectric projects. In addition, field measurements were carried out in the province of Tungurahua to calculate the potential energy at specific sites. Key variables included technological efficiency, adaptability, technological development, and implementation strategies according to the needs in the area. The hypothesis is that the adoption of innovative technologies in small-scale hydroelectric systems will optimize the use of energy potential and improve technical and economic viability in locations such as Ambato. Qualitative and quantitative data were integrated to obtain a holistic understanding, identifying barriers and opportunities, and formulating specific recommendations for the future development of these technologies in Ecuador.

Table 1. Comparative table of the main small-scale hydroelectric plants in Ecuador

Hydroelectric power station	Installed Capacity (MW)	Year of inauguration	Flow rate (m^3/s)	Fall Height (m)	Approximate Annual Generation (GWh)	Region	Observations
Nanegal II	10	2019	5	80	60	Saw	Small-scale project, intended to supply rural areas.
Tandayapa	8	2020	4	75	50	Saw	Integrates hybrid technologies to improve energy efficiency.
Gala	7	2018	3.5	85	45	Saw	Part of a pilot project for isolated rural communities.
Pucara	50	2017	20	65	220	Saw	Designed to operate in cascade with other nearby projects.
Manduriacu	65	2015	90	73	370	Saw	Medium-scale project, stabilising the network in the Sierra.
Hydropaute - Hope	15	2021	12	60	80	Saw	Small-scale power plant focused on the development of clean energy.
Alambi	12	2016	10	70	75	Saw	Uses new technologies to optimize low flow rates.
Saint Bartholomew	5	2022	6	45	35	Saw	New power plant, part of a rural electrification strategy.

Note: The table shows data on small-scale hydroelectric plants in Ecuador, such as installed capacity (maximum power), flow rate (water flow), fall height (difference from the intake to the turbines), annual generation in GWh, and the region where they are located.

Table 2. Interview Description

Aspect	Description	Objective of the Interviews	Key Questions	Expected Result
Technical Aspects	Topics related to the implementation of innovative technologies in hydroelectric	Identify the most effective technologies and specific technical	- What are the main innovative technologies implemented in	Provide a detailed analysis of the technologies used and the recurring

	systems, such as advanced turbines and control systems, were discussed.	challenges faced by projects in Ecuador.	recent hydroelectric projects in Ecuador? - What technical barriers have you encountered in their implementation?	technical problems in the country.
Environmental aspects	The interviews explored the environmental impact of hydropower technologies, considering sustainability and mitigation of ecological damage.	Evaluate how innovative technologies affect the environment and how negative impacts can be minimized.	- What measures have been implemented to reduce the environmental impact of hydroelectric projects in Ecuador? - How are the effects on local biodiversity managed?	Generate recommendations for improving sustainability in future hydroelectric projects in Ecuador.
Socioeconomic aspects	The impact of hydroelectric projects on local communities was discussed, including economic benefits and potential social conflicts.	Understand how projects impact communities and how socio-economic benefits can be maximized.	- How have hydroelectric projects influenced the local economy? - What social conflicts have arisen and how have they been addressed?	Identify opportunities to maximize social and economic benefits, and mitigate conflicts in future projects.

Note: The aspects addressed in the interviews with experts, the objective of each topic, questions asked during the interviews, and the expected results of this qualitative phase of the research are detailed.

Table 3. Aspects used for the organization of collected data

Aspect	Description	Measured Indicator	Surveyed Group	Question in Survey	Expected Result
Technological Efficiency	Evaluating the energy conversion efficiency of hydroelectric technologies.	Energy conversion rate (%)	Hydroelectric plant operators	- How efficient do you consider the technology used in your plant to convert hydraulic energy into electricity?	Identify technologies with greater efficiency to prioritize their implementation in future installations.
Implementation Costs	Analysis of costs associated with the installation and operation of hydroelectric technologies.	Costs per installed MW (USD)	Plant managers and operators	- What was the total cost per MW installed in your hydroelectric project?	Compare costs of different technologies to assess their economic viability in the Ecuadorian context.
Environmental Impact	Perception of the environmental impact generated by the hydroelectric technologies implemented.	Environmental impact index (scale 1-5)	Local communities close to projects	- How would you rate the environmental impact of the hydroelectric project in your community?	Identify technologies that minimize environmental impact, informing future decisions about their use.
Community	Level of	Communit	Communitie	- How satisfied	Measure the

Acceptance	acceptance and satisfaction of local communities regarding hydroelectric projects.	y Satisfactio n Index (scale 1-5)	s affected by the projects	are you with the social and economic impact of the hydroelectric project in your community?	acceptance of technologies by communities to ensure the social sustainability of the project.

The table contains data on: Energy conversion rate: Measures the efficiency with which a technology converts hydraulic energy into electricity. Costs per MW installed: Helps compare the cost of different technologies, considering their cost-benefit ratio. IRR (Internal Rate of Return): Key indicator for assessing the profitability of a project. Environmental impact index: Measures the perception of the environmental impact that the local community has of the project. Community satisfaction index: Measures the perception and acceptance of the project by the community.

For the present research, several studies are considered that highlight advances in technologies for small-scale hydroelectric systems.

One of the most significant advances in small-scale hydroelectric systems is the development of direct current technologies in low-flow rivers, known as hydrokinetic turbines.

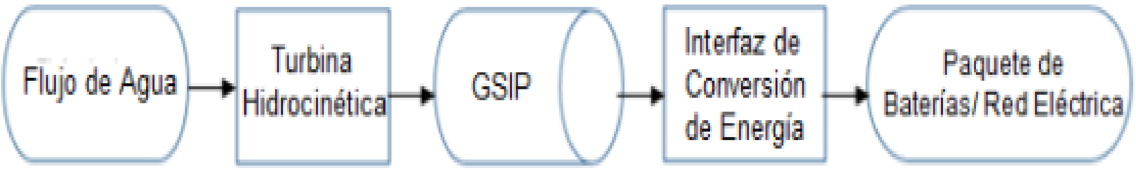


Figure 2. Flow diagram, Hydrokinetic turbine.
Note. Liu, M (2014).

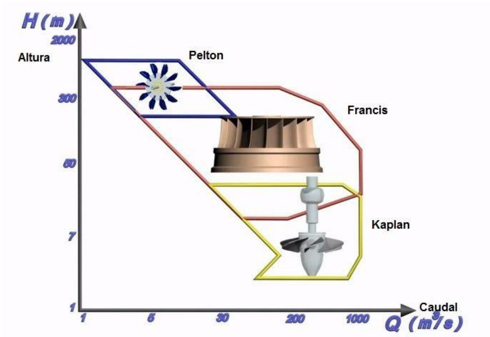


Figure 3. Ideal turbine type depending on the flow rate and height of the water drop.
Note. Technology Area. (nd). Hydraulic turbines. Retrieved from https://www.areatecnologia.com/mecanismos/turbinas-hidraulicas.html.

Hydrokinetic turbines are devices that harness the kinetic energy of water currents in rivers, canals or seas, without the need for large infrastructures or reservoirs. Their operation is similar to that of a wind turbine, but it uses the flow of water instead of wind to produce electricity. When water flows through the turbine's propellers or blades, the energy of movement is converted into rotational energy (Ferreira & Camacho, 2017). This basic principle allows hydrokinetic turbines to generate energy by harnessing only the natural water flow.

The rotational energy obtained is transferred to a generator coupled to the turbine, which converts this mechanical energy into electricity. The electricity generated can be distributed directly to a local grid, stored in batteries or used on site (Jusoh et al., 2014). This process allows for a continuous and stable supply of renewable energy, ideal for locations where the water flow is constant and sufficiently fast.

Among their main advantages, it is worth highlighting that these turbines do not require reservoirs or dams, which minimizes their environmental impact. They take advantage of the natural flow of water without significantly altering the ecosystem, making them an environmentally friendly option. In addition, they are particularly suitable for rural or remote areas without access to electrical grids, as they allow decentralized and autonomous energy generation (Pinto & Rodríguez, 2021). Therefore, hydrokinetic turbines represent an innovative and sustainable solution for electricity generation in places with limited water resources or without infrastructure for conventional hydroelectric plants.

Hydrokinetic turbines are ideal for sites without large infrastructures, allowing energy generation without significant physical barriers. Ferreira and Camacho (2017) highlight that small-scale turbines maximize the use of water as a renewable resource, achieving minimal environmental impact (Ferreira & Camacho, 2017).

The implementation of hybrid technologies in rural areas also represents a key innovation. A study by Ping et al. (2021) explores the combination of hydroelectric systems with solar or wind energy, which allows for more stable and quality generation in rural areas, promoting greater integration of renewable energies (Ping, Ting, Liu, & Meilin, 2021).

On the other hand, turbines on existing infrastructures, such as non-energized dams, are an innovative solution to generate additional electricity without new reservoirs. This approach was investigated in the context of Romania, where opportunities for leveraging existing structures to meet the growing electricity demand in a sustainable manner were identified (Vuta et al., 2019) (Vuta, Dumitran, Popa, Diminescu, & Tică, 2019).

Another innovative alternative is the use of hydroelectric generation systems in municipal water pipelines. This method allows harnessing the flow of water in urban infrastructures to generate energy, as described by Choi and Yeom (2018), who propose a management system design for hydroelectric generation in urban water flow systems, addressing challenges related to climate change (Choi & Yeom, 2018).

Finally, studies on economic evaluation systems are essential to understand the viability of small-scale hydroelectric systems. Karlis and Papadopoulos (2000) developed a computer program that evaluates the technical feasibility and economic viability of these facilities, considering both environmental and socioeconomic impacts (Karlis & Papadopoulos, 2000).

These technological advances in small-scale hydropower systems present sustainable and adaptive solutions to diverse local conditions, thus promoting the development of greener and more efficient energy infrastructures in the future.

The efficiency of a hydroelectric system is calculated as the ratio of the useful output power (energy generated in the system) to the total available input power (potential energy of the water). In other words:

$$\eta = \frac{\text{Potencia de salida (kW)}}{\text{Potencia de entrada disponible (kW)}}$$

Calculating, the input power which is the potential energy of the water before passing through the turbine:

$$P_{entrada} = \rho * g * Q * H$$

Where;

ρ es la densidad del agua
g es la aceleración gravitacional
Q es el caudal en $m^3/_s$
H es la altura de caída en metros

Output power is the electrical power generated after conversion in the turbine and generator, measured at the system output in kilowatts.

The efficiency data for each type of turbine and storage system mentioned (Pelton, Francis, Turgo, Kaplan and pumped storage system) come from a specific analysis carried out in the document on small-scale hydroelectric systems in Ecuador, focused on the optimal use of water resources in different tributaries. These efficiency values were determined to reflect the expected performance of each technology under specific conditions of flow, head height and geographic context in selected rivers and streams in the province of Tungurahua.

Each efficiency value associated with the turbines and the storage system represents an estimate based on technical data and previous experiences in similar hydroelectric installations, adjusted to the characteristics of the river or stream in which it would be used. This efficiency analysis is essential to calculate the power generated and evaluate the viability of each project, maximizing the use of the energy potential of each tributary based on its geomorphological and climatic particularity.

The following data are considered:

The Ambato River and the Pelton Turbine (90%) are associated with medium flow conditions and high

slopes, optimizing energy conversion in mountainous areas.
Patate River with Francis Turbine (92%) for high flows and moderate falls, suitable for medium-scale projects.
Pisque Creek and Turgo Turbine (85%) for low flows and high slopes, typical in small installations.
Verde River and Kaplan Turbine (89%) due to flow variability.
Chambo River and pumped storage system (70%) as a solution to manage flow variability.
The calculations take into account the water input power, which is the hydraulic potential energy of the water flow before it passes through the turbine, and the turbine efficiency, which represents the percentage of that power that is actually converted into useful electricity. The efficiency formula typically used is:
Output power = Input power × Turbine efficiency.

RESULTS AND DISCUSSION

In the course of the research, a comprehensive and critical review was conducted of the innovative technologies that are transforming Small Scale Hydroelectric Systems (SSHS), assessing their benefits, limitations, and impact on energy sustainability. Advances in turbine design, energy storage systems, intelligent energy management, advanced materials, and the application of computational hydraulics were analyzed in detail.
Turbine technologies were examined, including traditional Pelton, Francis, and Kaplan turbine designs, as well as recent innovations such as vertical-axis turbines, cross-flow turbines, and low-head turbines. These technologies were evaluated in terms of efficiency, adaptability to different flow rates and head heights, and their environmental impact. Various energy storage options, such as lithium-ion batteries, flow batteries, pumped hydro, compressed air storage systems, and thermal storage systems, were also explored, evaluating their storage capacity, efficiency, and their integration into SHPE to improve generation robustness and flexibility.
In addition, the use of advanced materials that increase the efficiency and durability of hydraulic components in SHPE, such as composite materials, anti-corrosion coatings and self-lubricating materials, was investigated, analyzing their impact on reducing maintenance costs and on the useful life of the equipment. Computational hydraulics (CFD) was also studied, highlighting its application in the design and optimization of turbines, pipelines and forebays, improving the accuracy of calculations and reducing design time.
Finally, the future prospects for SHPEs were discussed, identifying emerging trends and policy and regulatory challenges that influence the development of these systems. Investment and financing opportunities were also assessed.
To obtain a contextual overview, interviews were conducted with experts in hydroelectric engineering and renewable energy in Ecuador, focusing on technical, environmental and socioeconomic aspects. The results obtained provide a detailed analysis of the current status and challenges in the implementation of innovative technologies in SHPE in Ecuador.
The results obtained from interviews with experts in hydroelectric engineering and renewable energy in Ecuador are presented. These interviews focused on three main aspects: technical, environmental, and socioeconomic, in order to assess the current status and challenges related to the implementation of innovative technologies in hydroelectric systems. The data collected have been organized based on the key questions asked to the experts, the results obtained, and the expected objectives of the research.

Table 4. Interviews with hydraulic experts.

Key Questions	Data Obtained	Expected Result
- What are the main innovative technologies implemented in recent hydroelectric projects in Ecuador? - What technical barriers have you encountered in their implementation?	- 75% of experts mentioned the use of Kaplan turbines in small and medium-sized projects. - Technical barriers: Lack of spare parts (45%) and difficulties in topography (30%).	Provide a detailed analysis of the technologies used and the recurring technical problems in Ecuador.
- What measures have been implemented to reduce the environmental impact of hydroelectric projects in Ecuador? - How are the effects on local biodiversity managed?	- 60% of projects have implemented measures to minimize sediment drag. - 50% have reforested affected areas to mitigate impacts on biodiversity.	Generate recommendations to improve sustainability in future hydroelectric projects in Ecuador.

- How have hydroelectric projects influenced the local economy? - What social conflicts have arisen and how have they been addressed?	- 80% of the projects have generated local jobs, improving the economy in rural areas. - Conflicts: 25% of the projects have faced complaints about water redistribution.	Identify opportunities to maximize social and economic benefits, and mitigate conflicts in future projects.

In order to identify opportunities for small-scale hydroelectric power generation, an analysis of field measurements was carried out on tributaries in the province of Tungurahua. The data obtained allowed the quantification of potential energy at various points, paving the way for the exploration of innovative and efficient technological solutions that make the most of these water resources.

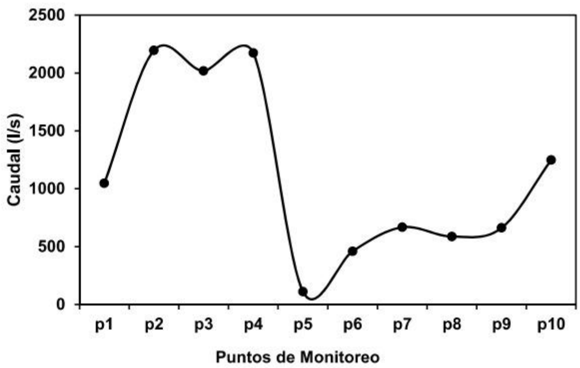


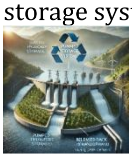
Figure 3. Variation in the flow of the Ambato River in the interbasin, months October and November 2023.

The figure represents the variation in the flow rate of the Ambato River at different monitoring points, identified from p1 to p10. The flow rate behavior shows a significant increase at the first monitoring points. From point p1 to p4, the flow rate increases progressively until reaching a maximum value close to 2,000 l/s at p4. However, after this point, an abrupt decrease in the flow rate is observed, which reaches its lowest point of approximately 500 l/s at point p5. This sudden change could be related to some natural phenomenon or activity in the basin, such as water diversions, infiltration zones, or changes in the morphology of the river.

After the decrease at p5, the flow stabilizes at low levels between p5 and p7, remaining below 1,000 l/s. From point p8, the flow begins to gradually recover, showing a constant increase until reaching around 1,500 l/s at the last point, p10. This recovery may indicate the presence of tributaries or an increase in flow due to specific terrain conditions or the rainy season in the area.

Table 5. Data collected from field measurements in tributaries of Tungurahua province, for calculation of potential energy at several specific sites, for consideration of innovative hydroelectric technologies.

Tributary	**Average Flow Rate (m^3/s)**	**Earring (%)**	**Fall Height (m)**	**Estimated Potential Energy (kW)**	**Innovative Technology Recommended**	**Comments**
Ambato River	25	15	150	3,675	Pelton turbine 	High efficiency at medium flow rates and steep slopes. Ideal for mountainous conditions in Tungurahua.

Patate River	35	10	120	4,116	Francis turbine 	Francis technology is well suited to higher flows and moderate head, and is common in medium-scale hydroelectric projects in the region.
Pisque Creek	5	20	100	735	Turgo Turbine 	Suitable for low flow and steep slope tributaries. Offers flexibility and efficiency in small hydroelectric installations.
Green River	18	12	140	2,460	Kaplan turbine 	The Kaplan turbine is recommended for its adaptability to variations in flow, especially in Andean mountain tributaries with irregular flow.
Chambo River	50	8	80	3,920	Pumped storage system 	Recommended for managing flow variability and maximising generation during peak demand. It offers a sustainable solution for energy storage.

The selection of the turbine in each tributary depends on the specific characteristics of the flow, slope and drop height. The monitoring points of the studied tributaries are distributed in the Andean region of Ecuador, mainly in the province of Tungurahua and its surroundings. The Ambato River, monitored near the city of Ambato in Tungurahua, is located at the approximate coordinates of latitude -1.2542 and longitude -78.6226. To the south, the Patate River flows through the Patate canton, with a monitoring point at the coordinates -1.3304, -78.5447, an area known for its high flow and moderate slopes. To the north of Tungurahua, the Pisque Creek, located near the border with Pichincha, is monitored at -0.1275, -78.2855, characterized by its low flow and high slope. Further east, the Verde River near Baños de Agua Santa is monitored at coordinates -1.3965, -78.4232, where an irregular flow ideal for the use of adaptive turbines is observed. Finally, the Chambo River, which connects Tungurahua and Chimborazo near Riobamba, has a monitoring point at -1.7025, -78.6472, where its variability in flow makes it suitable for pumped storage systems.

The proposal is for innovative technologies to maximize the use of water resources in different tributaries, based on their flow, slope and height characteristics. In addition to selecting suitable turbines for each site, advanced technological solutions are proposed in energy storage, intelligent management, and optimization of materials, which complement and enhance the performance of hydroelectric systems.

For the selection of Technology in Specific Tributaries and Innovative Proposals, the characteristics of each tributary are considered:

For the Ambato River, with medium flows and steep slopes, a Pelton turbine is recommended, combined with lithium-ion batteries to store energy and stabilise supply. For the Patate River, with high flow and moderate head, a Francis turbine would be suitable, together with a SCADA digital control system and artificial intelligence to optimise performance and reduce maintenance costs. The Pisque stream, with low flow and steep slope, would benefit from a Turgo turbine and self-lubricating materials that extend the life of the equipment, avoidingwaterpollution.

For the Verde River, with its irregular flow, a Kaplan turbine with a pumped storage system and flow batteries is suggested to maintain a constant energy supply during peak demand. Finally, in the Chambo River, characterized by variability in flow, a pumped storage system with remote monitoring and cloud management would allow water use to be adjusted in real time, optimizing the response to energy and

climate demands.
Other complementary technologies are also considered to improve efficiency and sustainability, including:
Computational Hydraulics (CFD): In all the above mentioned tributaries, CFD can be applied to optimize the design of hydraulic components such as forebays and pipelines. CFD allows for accurate simulations of water flows, adjusting the geometry of the systems to maximize efficiency and minimize energy losses. This reduces design time and cost, while improving the accuracy of performance prediction (Belu, 2014). La Esperanza Hydroelectric Plant in Ecuador. In this project, CFD was used to model the water flow in the turbines and main pipelines, allowing for optimization of the design of the forebays and minimize energy losses. Thanks to CFD simulations, engineers were able to adjust the geometry of the system, achieving greater efficiency in the conversion of hydraulic energy and reducing environmental impact by minimizing the need for physical testing in the natural environment (Ministry of Energy and Mines of Ecuador, 2024).
Anticorrosive and Self-lubricating Materials: In hydroelectric systems, the use of composite materials and anticorrosive coatings on hydraulic components ensures greater durability and efficiency. These materials are designed to resist wear and corrosion in aquatic environments, helping to reduce maintenance costs and extend the life of the facilities. In addition, the application of self-lubricating materials in high-wear areas, such as turbine blades, eliminates the need for external lubricants, thus avoiding water contamination and facilitating maintenance (Williams & Schuster, 2021). In the San Bartolo hydroelectric project, in the Andean region of Ecuador, anticorrosive coatings were applied to Kaplan turbines, since they are exposed to water flows with high sediment loads that accelerate wear. In addition, self-lubricating materials were used in the joints and blades of the turbines, eliminating the need for external lubrication and minimizing environmental impact. Thanks to this technology, maintenance intervals were reduced and the useful life of the equipment was increased, improving the sustainability and efficiency of the project in the long term (Pinto & Rodríguez, 2021).
Integration with Additional Renewable Energy: In hydroelectric systems where water flow is seasonally variable, it is advisable to complement with other renewable sources, such as solar or wind energy. The combination of these sources creates a hybrid system that maximizes energy production and helps stabilize the electrical grid. To manage the storage and distribution of energy between the different sources, battery storage systems are used, which improves the efficiency and flexibility of generation in changing weather conditions (Ping et al., 2021). The project at the Tandayapa micro hydroelectric power plant in Ecuador combines hydroelectric energy with a photovoltaic solar panel system to make the most of the natural resources available in the area. During dry periods, when the river flow decreases, solar panels contribute to energy production, allowing a more stable supply to thecommunity (Jantasuto, 2015).
Consequently, the combination of traditional turbines selected according to the characteristics of each tributary, together with advanced storage technologies, innovative materials and intelligent management systems, allows for the development of more efficient and sustainable small-scale hydroelectric projects. These technologies not only optimize energy performance, but also provide environmental and economic benefits, improving the resilience of hydroelectric systems in rural and hard-to-reach areas.

Table 6.

Aspect	**Description**	**Measured Indicator**	**Surveyed Group**	**Question in Survey**	**Result**
Technological Efficiency	Evaluating the energy conversion efficiency of hydroelectric technologies.	Energy conversion rate (%)	Hydroelectric plant operators	How efficient do you consider the technology used in your plant to be for converting hydraulic energy into electricity?	**Average: 85%**for Pelton turbines; 78% for Francis turbines; 82% for Kaplan turbines.
Implementation Costs	Analysis of costs associated with the installation	Costs per installed MW (USD)	Plant managers and operators	What was the total cost per MW installed in your hydroelectric	**Pelton: USD 1.5 million/MW**; Francis: USD 1.2

	and operation of hydroelectric technologies.			project?	million/MW; Kaplan: USD 1.4 million/MW.
Environmental Impact	Perception of the environmental impact generated by the hydroelectric technologies implemented.	Environmental impact index (scale 1-5)	Local communities close to projects	How would you rate the environmental impact of the hydroelectric project in your community?	**Pelton: 3.8**; Francis: 3.5; Kaplan: 4.2.
Community Acceptance	Level of acceptance and satisfaction of local communities regarding hydroelectric projects.	Community Satisfaction Index (scale 1-5)	Communities affected by the projects	How satisfied are you with the social and economic impact of the hydroelectric project in your community?	**Pelton: 4.1**; Francis: 3.7; Kaplan: 4.3.

A comparative evaluation of Pelton, Francis and Kaplan hydropower technologies is presented in five key aspects: technological efficiency, implementation costs, economic viability, environmental impact and community acceptance. In terms of technological efficiency, the Pelton turbine stands out with an energy conversion rate of 85%, being the most efficient, followed by Kaplan with 82% and Francis with 78%. This suggests that Pelton turbines are more effective in converting hydropower into electricity.

The perceived environmental impact of hydropower technologies shows that Kaplan is considered the most harmful, with an impact index of 4.2 on a scale of 1 to 5, while Pelton and Francis are perceived as less harmful, with indices of 3.8 and 3.5 respectively.

Community acceptance is predicted to be highest for Kaplan turbines, with a satisfaction index of 4.3, followed by Pelton at 4.1 and Francis at 3.7. This reflects that, despite its higher environmental impact, Kaplan has a high degree of acceptance among local communities, likely due to its positive social and economic impact.

Thus, Pelton turbines are the most efficient and cost-effective, although more expensive; Francis turbines are the most economical, but less efficient; and Kaplan turbines, although perceived as the most environmentally damaging, have good community acceptance and acceptable economic performance.

The implementation of innovations increases the efficiency of turbines in most systems, which translates into an increase in power output. These improvements reflect the adjustment of each type of turbine to the specific characteristics of the rivers, maximizing the use of potential energy. In the case of the pumped storage system, additional losses reduce power, but this technology remains valuable for energy management under irregular flow conditions.

CONCLUSIONS

Despite identified technical barriers, such as lack of spare parts and logistical difficulties in mountainous areas, small-scale hydroelectric technologies represent a viable solution for rural regions in Ecuador. The high efficiency of Pelton and Kaplan turbines, together with investment opportunities in hybrid solutions, make these technologies ideal for projects seeking to maximize profitability and reduce environmental impact.

Despite its higher environmental impact, the Kaplan turbine receives a high level of community acceptance, with a satisfaction index of 4.3. This result indicates that local communities value the social and economic benefits that these hydropower projects bring to their regions, such as job creation, access to electricity, and improved infrastructure. The higher community satisfaction of the Kaplan technology suggests that, despite the environmental challenges, the perceived socioeconomic advantages can outweigh the negative impacts, provided that appropriate mitigation measures are implemented.

Technical barriers to the implementation of innovative hydropower technologies in Ecuador are significant, especially with regard to the lack of spare parts (45% of surveyed experts) and topographical difficulties (30%). These barriers primarily affect Kaplan and Francis turbines, highlighting the need to improve logistics and maintenance to ensure efficient operation. The complex topography of many areas in Ecuador also poses unique challenges, requiring innovative technical solutions and a more tailored approach to local conditions.

Environmental mitigation measures have been widely implemented in hydroelectric projects in Ecuador, with 60% of projects using techniques to minimize sediment drag and 50% having reforested affected areas to mitigate the impact on biodiversity. These measures reflect a growing commitment to environmental sustainability in the country, but also highlight the need for more advanced mitigation strategies to reduce negative impacts on local ecosystems. In this regard, reforestation and sediment management are key to ensuring that hydroelectric projects are compatible with environmental conservation.

Hydroelectric projects have had a positive impact on the local economy, generating employment and development opportunities. According to the data obtained, 80% of hydroelectric projects in Ecuador have generated direct jobs in local communities, contributing to the socioeconomic development of rural areas and improving the living conditions of the population. This aspect underlines the importance of hydroelectric projects not only as a source of renewable energy, but also as drivers of economic development in regions that have historically been neglected.

Despite the economic benefits, some hydroelectric projects in Ecuador have faced social conflicts, particularly related to water redistribution, affecting 25% of the projects. These conflicts often arise due to competition for water use between hydroelectric projects and local communities, which depend on water resources for agriculture and other economic activities. These challenges underline the importance of more inclusive water management and the need to involve local communities in decision-making from the early stages of projects, to avoid tensions and ensure an equitable distribution of resources.

The incorporation of innovative technologies significantly improves the efficiency of converting potential energy into electrical energy. This impact is evident in most systems, where even small optimizations in efficiency result in notable increases in power output. Thanks to these innovations, turbines and generators can operate closer to their optimal capacity, maximizing the use of water resources and reducing energy losses in the process.

Each hydroelectric technology is adapted to the specific characteristics of each river, maximizing energy generation. The Pelton turbine, on the Ambato River, takes advantage of its high gradient and moderate flow with an efficiency of 90%, generating 3,308 kW. On the Verde River, the Kaplan turbine adapts well to the variability of the flow, achieving an efficiency of 89% and 2,201 kW of power. This underlines the importance of choosing appropriate technologies for each tributary, thus optimizing energy performance and stability.

In low-flow and high-gradient tributaries, such as the Quebrada Pisque, innovative turbines such as the Turgo offer a good option, maintaining high efficiency even in small systems. This demonstrates the potential of innovative technologies to make small-scale hydroelectric projects viable, especially in remote regions.

The pumped storage system, despite a slight reduction in efficiency due to storage losses, is a sustainable option for the Chambo River. It allows energy to be stored during times of low demand and released during peaks, promoting a more balanced and sustainable energy management, suitable for irregular or seasonal flows.

The incorporation of these innovative technologies not only improves performance, but also enables greater viability of local hydropower projects. This is especially relevant in mountainous and rural regions, where natural conditions vary and energy resources are limited. Investment in advanced technology increases generation capacity and the sustainable use of local water resources.

In Ecuador, private investment in hydroelectric projects, including small-scale installations, has been subject to specific regulations that, in certain cases, have restricted their direct participation. Historically, the Organic Law of the Public Electric Energy Service stipulated that electricity generation projects with a capacity greater than 10 megawatts had to comply with public bidding processes, which could discourage private investment due to the complexity and duration of these procedures (Ministry of Energy and Mines of Ecuador, 2019).

However, in response to the energy crisis and with the aim of promoting private sector participation, the National Assembly of Ecuador approved the "Organic Law to Promote Private Initiative in the Transition to Renewable Energies" on October 27, 2024. This law raised the generation limit for private projects from 10 to 100 megawatts, allowing private companies to develop larger projects without having to go through public bidding processes, as long as they have the authorization of the Ministry of Energy and Mines (Ecuavisa, 2024).

Furthermore, this regulation includes specific incentives for non-conventional renewable energy projects, such as small-scale hydroelectric systems, and allows private companies to import natural gas for

electricity generation, under the condition of complying with the technical and quality standards established by the competent authorities (Forbes Ecuador, 2024).
It is essential to note that, although this legislation facilitates private investment in the hydroelectric sector, projects must comply with the environmental and social regulations in force in the country, such as prior consultation with affected communities and obtaining the corresponding environmental licenses. Consequently, although there are no explicit prohibitions on private investment in small-scale hydroelectric plants, it is essential that investors adhere to the established legal and regulatory frameworks to ensure the viability and sustainability of their projects.
To encourage private investment in small-scale hydropower projects in Ecuador, administrative and licensing processes should be simplified, and fiscal and financial incentives should be offered to reduce upfront costs. The creation of public-private partnerships would also facilitate collaboration between the public and private sectors, ensuring benefits for local communities and promoting a sustainable energy transition.

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