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TECHNICAL NOTE N.7

OVERVIEW OF HYDROPOWER IN LATIN AMERICA AND THE CARIBBEAN

Energy joins us

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Organización Latinoamericana de Energía (OLADE)

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1. Introduction

Hydroelectric generation, which harnesses the energy of moving water to produce electricity, has been a key source of renewable energy for decades. As the global community confronts the need for an energy transition and the decarbonization of the energy matrix, this technology is becoming even more relevant. This technical note explores its importance, its contribution to the world's electricity generation—and in the Latin American and Caribbean region—as well the challenges it faces in the current context.

Hydropower is one of the cleanest and most sustainable energy sources, capable of delivering large amounts of energy consistently and reliably, making it an essential component of global energy infrastructure.

In times of energy transition—where the goal is to reduce reliance on fossil fuels and lower carbon emissions—hydropower plays a crucial role. Its capacity to generate energy without direct carbon emissions makes it an essential instrument in the fight against climate change. Moreover, hydropower plants can serve as energy storage systems, facilitating the integration of intermittent renewable sources such as solar and wind.

Another significant advantage of hydroelectric power plants—particularly those with greater regulatory capacity—is their ability to provide flow regulation services for other water uses. These include essential needs, such as human supply and animal watering, as well as supporting agricultural irrigation in times of increasingly frequent water crises.

It is also noteworthy that several studies indicate that countries with greater storage capacity—and therefore are more resilient to climate variability—also experience greater economic benefits.

Despite its benefits, hydropower also faces significant challenges. The most notable include:

- Environmental Impact: The construction of dams and reservoirs can disrupt aquatic and terrestrial ecosystems and may lead the displacement of local communities.
- Climate change: Variability in precipitation patterns due to climate change can impact water availability, thereby affecting generation capacity.

- Investments and Costs: The development of hydroelectric projects requires significant investments and long construction timelines.
- Maintenance and Modernization: Many existing hydroelectric plants are old and require modernization to enhance efficiency and reduce environmental impacts. flexibilidad[1]

The International Energy Agency [1], in the Stated Policy Scenario (STEPS), states that global short-term electricity system flexibility[1] needs are projected to more than triple by 2050 compared to current levels. In the Announced Pledges Scenario (APS), Will be double by 2030 and increase 4.5 times by 2050.

The rapidly increasing share of solar photovoltaic energy emerges as the key factor driving the rise in short-term flexibility needs; wind power is less variable in the short term, but can fluctuate significantly over weeks or seasons, becoming a major contributor to seasonal flexibility needs as its share in global electricity systems increases. While wind and solar production patterns may be complementary to fluctuations in electricity demand, their growing share tends to increase overall system flexibility needs.

Increasing flexibility needs and changes in the global power plant fleet (with coal phase-out without reduction in many regions) mean to reduce the proportion of short-term flexibility provided by thermal power plants falls from around 60% today to just one-third by 2030 in the APS. Thermal power plants—including fossil fuel plants without reduction and low-emission technologies such as nuclear, fossil fuels with carbon capture, utilization and storage, bioenergy, hydrogen and ammonia—will remain as key providers of seasonal flexibility until 2040. By 2050, the share in the flexibility mix will be reduced to around 10% [1]. The relative participation of hydropower in supplying short-term flexibility diminishes as demand increases rapidly, but remains as an important source of seasonal flexibility, and is the main source of the seasonal equilibrium required after 2040. Market designs and regulations must ensure that the supply of pumped storage, reservoir hydropower,

[1] Flexibility, according to IEA, is defined as the ability of an electric system to reliably and cost-effectively manage demand and supply variability. It ranges from ensuring instant stability of the electricity system to supporting long-term security of supply.

and other forms of long-term energy storage aligns with the system's long-term flexibility needs.

Given the global goal of tripling renewables, and also because of the challenges of providing flexibility to new systems, hydroelectric power plants must play a central role in the countries energy expansion plans.

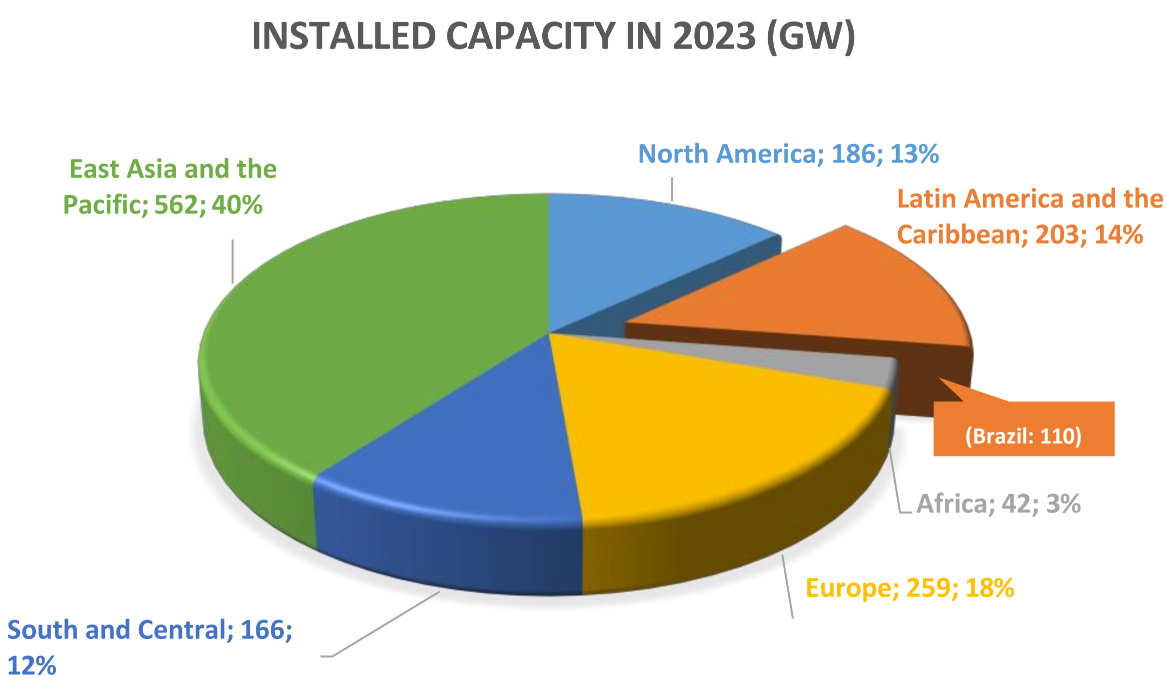
Hydropower is a fundamental source in the global energy matrix, particularly in the context of the energy transition and decarbonization. Despite the challenges it faces, its benefits—in terms of sustainability and storage capacity—position it as a vital contributor in building a cleaner and safer energy future.

2. Global and Latin American and Caribbean Overview of Hydropower

2.1. Hydropower in the world

Globally, hydropower accounts for approximately 16% of total electricity generation and around 70% of all renewable energy generated, in 2023 there would be 1,416 GW of installed capacity [2]. Countries such as China, Brazil, Canada, the United States and Russia are global leaders in installed hydroelectric capacity. The large scale of many of their hydropower plants enables the reliable supply of electricity to millions of homes and businesses, making hydropower an essential pillar in the energy matrix of many countries. Figure 1 shows the global installed capacity by subregion in 2023:

Figure 1: Global hydropower installed capacity for 2023



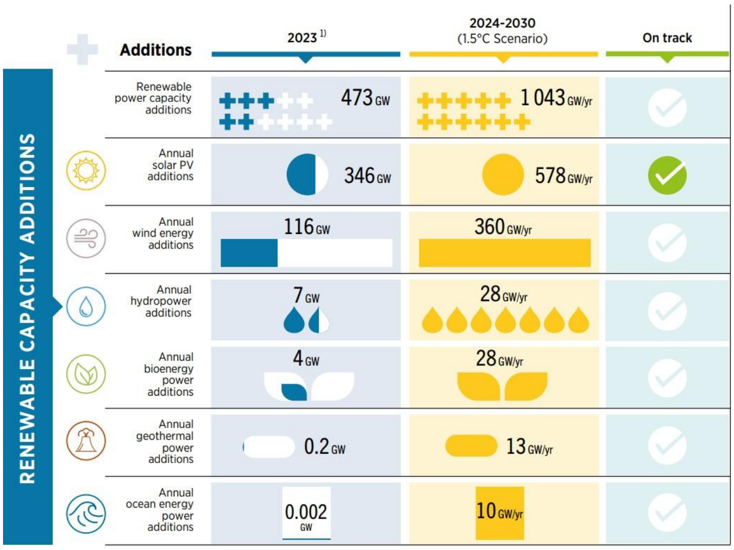
Source: Own elaboration based on: "Panorama mundial de la energía hidroeléctrica. Oportunidades para fomentar emisiones netas iguales a cero. IHA, 2024" [1], with OLADE data for LAC (https://sielac.olade.org/).

Efforts towards the energy transition also bring challenges related to the generation profile of new sources, alongside growing concerns about energy security and sovereignty. As renewable sources advance, demands for flexibility also increase—intensifying discussions about firm sources of storage and generation.

In all IEA scenarios, peak demand is projected to increase faster than total electricity demand, and up to 80% faster in emerging market and developing economies by 2035. Efficiency measures—such as improved insulation and more efficient appliances—help prevent a larger increase, along with measures that allow for demand flexibility, including smart meters and dynamic tariffs. Batteries become essential for dispatchable capacity. Natural gas and coal plants continue to play a significant role in providing dispatchable capacity in emerging and developing markets economies, but the majority of the short-term flexibility is expected to be met by batteries and demand.

IRENA in [3] also highlight numerous challenges to achieve the agreed decarbonization goals. The table below presents the challenges of installing renewable installed capacity in the coming decades.

Figure 2: Additional Renewables Capacity



Source: IRENA, 2024

Investment in clean energy is on the rise, but it needs to be further intensified to meet the energy and climate goals set by LAC countries. In a record year for renewables, 2023 added 27 GW of solar photovoltaic and wind capacity—driven by installations in Brazil (20 GW). [4]

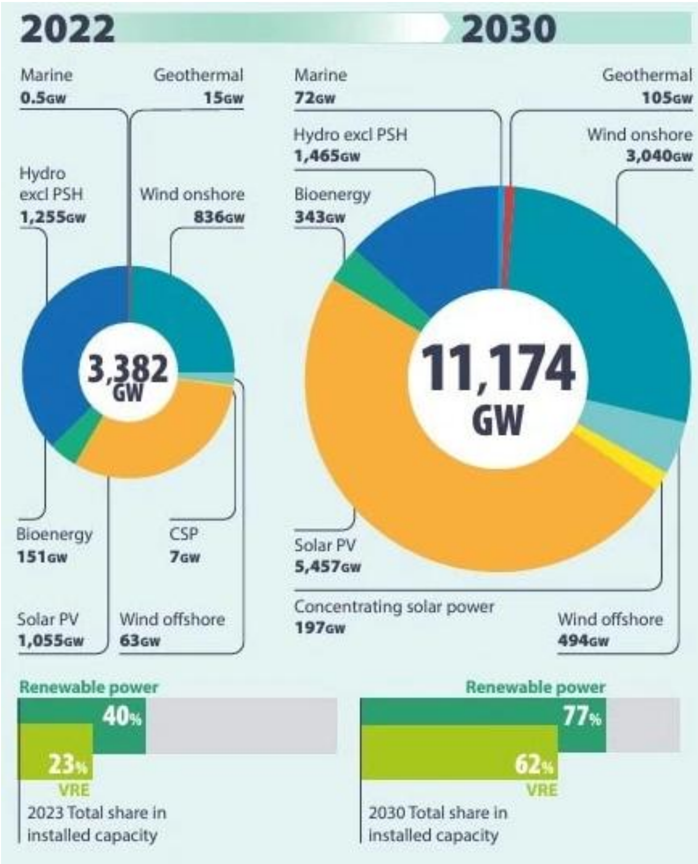
The International Hydropower Association (IHA) offers a series of recommendations for decision-makers in [2]. Great efforts should be pursued in sustainable hydropower planning, securing adequate financing for projects and in pursuing innovations and new hydropower technologies.

This important document presents:

> "Both the International Energy Agency (IEA) and the International Renewable Energy Agency (IRENA) estimate that achieving net-zero emissions by 2050 will require approximately double the current global hydropower capacity. So, what is the path between the present and that future? IRENA's net-zero emissions projection for 2050 envisages a total hydropower capacity of more than 2900 GW with nearly 420 GW coming from PSH. Bridging the gap between current installed capacity and these figures, will require to add about 46 GW per year. The 2030 projection that served as the basis for the campaign to triple renewables suggested lower near-term growth for hydropower—rising from 1,255 GW in 2022 to 1,465 GW in 2030 (excluding PSH)— which would require a growth rate slightly higher than 26 GW per year. This would leave approximately 1,000 GW of non-PSH capacity to supply over the period 2030-2050, or around 50 GW per year, plus about 10 GW per year of additional PSH."

The figure below, taken from the referenced IHA publication, highlights the challenges associated with the expansion of renewable energy sources.

Figure 3: Current installed renewable energy capacity and 2030 projection



Source: IHA with data from IRENA.

Considering these references, it is clear that there is demand for initiatives that support the accelerated development of hydroelectric power plants globally that can adequately meet the requirements presented.

2.2. Hydropower in LAC

In 2023, LAC had 203 GW of installed hydropower capacity, representing 39% of the region's total installed capacity [4], and this source accounted for 45% of generation in 2023.

Table 1 – Installed Capacity for OLADE member countries and estimated potential

OLADE Member Countries	Installed Capacity (MW)	Estimated Potential (MW)
Argentina	11359	40400
Barbados	-	-
Belice	55	900
Bolivia	759	40000
Brazil	109922	172000*
Chile	7591	25156
Colombia	13206	56188
Costa Rica	2372	7034
Cuba	65	650
Ecuador	5192	21900
El Salvador	638	2258
Grenada	-	-
Guatemala	1514	5000
Guyana	-	7000
Haiti	78	207
Honduras	917	5000
Jamaica	29	86
México	12612	53000
Nicaragua	158	2000
Panamá	1845	2955
Paraguay	8760	13013
Perú	5544	69445
Dominican Republic	623	2095
Suriname	189	2420
Trinidad & Tobago	-	-
Uruguay	1538	1815
Venezuela	18246	58000
TOTAL	**203210**	**416522**

Source: Own elaboration. Installed capacity based on SIELAC data, reference: January 2023 and Estimated Potential (without hydraulic storage systems) as of [5] 2018, with updated Brazil data from EPE

Latin America's vast hydroelectric potential began to be harnessed in the late 19th century, with Brazil (1883), Guatemala (1884) and Costa Rica (1884) among the pioneering countries. Between 1890 and 1900 several other countries across the region installed their first hydroelectric plants [5] This early development of hydropower spurred the creation of electricity companies—primarily state-owned—that play a central role in Latin American hydroelectric development, such as the CFE of México (1937), ENDESA in Chile (1944), AyE in Argentina (1947), ICE in Costa Rica (1949), EPM in Colombia (1955), CHESF (1945), Furnas (1957) and ELETROBRAS (1962) in Brazil, ENDE in Bolivia (1962), ELECTROPERU in Perú (1972), among others.

The evolution of hydroelectric generation has varied among the countries of the region and over time. Nevertheless, its development allowed the extension of transmission systems, and the creation of local technical capacity. It is important to highlight that this period was marked by a growing public and state involvement in both the development and its financing. Within this context of broad public participation, this stage was also characterized by the preparation of several hydroelectric inventory studies, and the development of studies of large-scale projects, many of which would be implemented in the decades that followed.

After the oil crisis of the 1970s, the hydroelectric sector experienced renewed momentum, leading to the development of major projects (even binational). This period marked a significant moment for hydroelectric expansion.

As foreseen in [5], the historical development of the hydroelectric sector in the region prioritized sites offering greater economic profitability, lower cost, and/or reduced socio-environmental impact. Nevertheless, given the geographic extension of several countries, projects development was also determined by the proximity of these to the demand centers. A clear example is Brazil, where the hydroelectric potential of the Southeast region—located near the demand centers—was developed early on. In contrast, the Amazonian potential only began to be exploited in a second period, made possible by the construction of high-voltage lines.

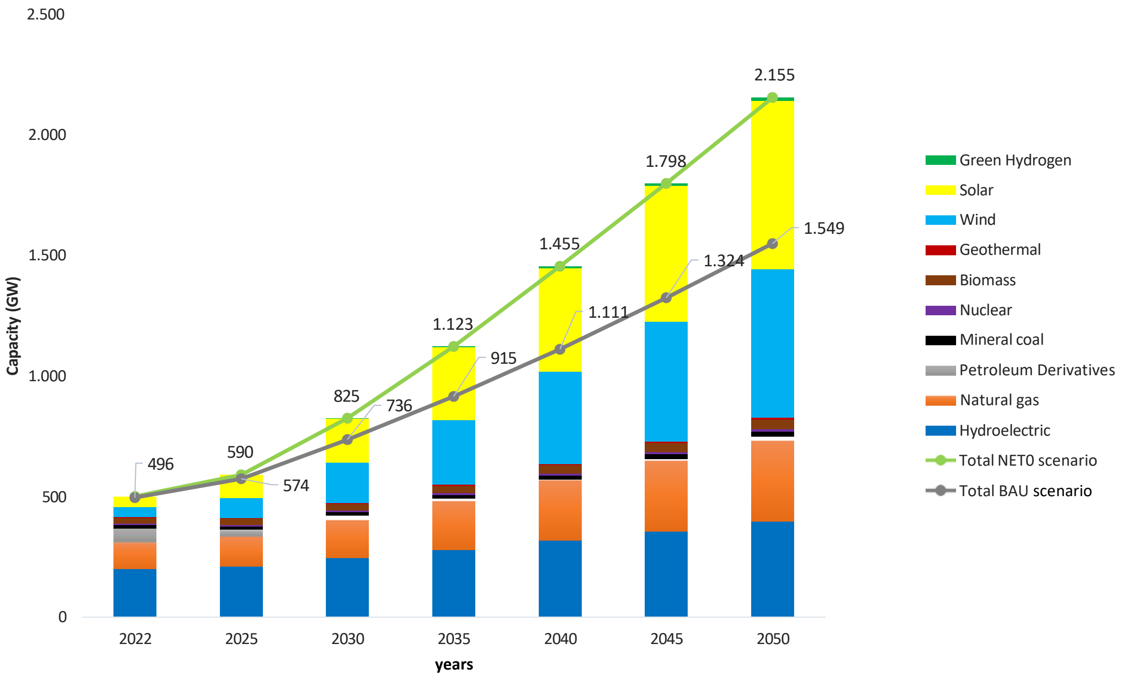
The total estimated hydropower potential for the region is approximately 416 GW. Nevertheless, this figure should be viewed as a reference rather than an absolute value, as the accuracy of some countries varies depending on the extent of studies and the methodologies used for the inventory of the hydroelectric resource. However, this estimate does not yet account for the potential associated with the hydraulic storage systems, due to absence of updated studies and also the wide range of possible arrangements of waterfalls and reservoirs to be built.

According to the IHA in [2], several major projects are currently under development, including the 7,550 MW Manseriche project in Peru, the 3,600 MW Zamora G8 project announced in Ecuador, and the 2,400 MW Ituango project under construction in Colombia. Nevertheless, it is essential to prioritize the development of supportive policies to take advantage of opportunities.

An essential discussion concerns the adequacy of remuneration of hydroelectric plants in accordance with the new services provided in modulation to complement the intermittent generation of wind and solar energy. This new mode of operation—characterized by greater variability— is not always aligned with the design of existing hydroelectric plants. Many of which were designed and sized to operate as baseload generation, delivering constant power output and producing energy at optimal efficiency under specific height and flow conditions. Operating hydroelectric power plants outside their optimal efficiency point—mainly with constant changes in their output—can impose stress on mechanical elements, increasing wear and tear, accelerating aging and reducing efficiency. [5]. Not to mention the potential environmental costs associated with altering downstream flow conditions of plants that begin to generate more frequent and pronounced flood waves. These changed can negatively impact other water uses. Addressing these impacts requires negotiation with environmental agencies of water resources, civil defense, municipalities, and others. This may result in legal proceedings that pose risks to plant concessionaires.

In its 2024 LAC Energy Outlook [4], OLADE presents studies of decarbonization scenarios for 2050 (NET0) and the evolution of installed capacity under these scenarios. The expansion of installed capacity electricity generation in LAC corresponds mainly to the increase in the capacity of wind, solar photovoltaic and thermal plants powered by natural gas. Due to the increased electricity demand from end-use sectors and in the green hydrogen production industry, the installed capacity in LAC in 2050 is 39% higher in the NET0 scenario compared to the value projected in the BAU scenario for the same year. Figure 4 below illustrates the result of this expected expansion for a NET0 scenario. In this deep decarbonization scenario of the energy sector for Latin America and the Caribbean, the installed capacity of hydroelectric plants is expected to grow by 96% by 2050.

Figure 4: Projection of installed electricity generation capacity, LAC



3.Modernization and Expansion of Hydropower plants

With more than 50% of the installed capacity in the LAC region exceeding 30 years of operation, there is an opportunity to modernize these assets in order to increase their capacity and climate resilience.

According to [6], the performance of hydroelectric machinery declines over time due accumulate wear and tear and affects generation performance, reducing the efficiency and interfering with power supply. Nevertheless, this trend can be reversed through actions for repowering, modernization, and the expansion of existing plants.

Repowering/modernization begins with interventions in plant machinery, aiming to increase installed power, increasing efficiency, among other improvements.

Expansion can be achieved by additional new machines or by building a new power plant.

San José Declaration on Sustainable Hydropower [7], the final manifesto of the 2021 World Hydropower Congress, emphasizes the need for investment in modernizing the existing hydropower fleet as an essential part of the global energy transition, as well as recognizing and compensating for flexibility, reliability, and storage services.

Currently, there are significant challenges related to the management of the hydroelectric fleet, and investments remains limited for enabling capacity upgrades and performance improvements of the existing plant.

4.Hydraulic Storage Systems

Hydraulic Storage Systems or Pumped Storage Hydropower (hereinafter PSH) are a promising technology for energy storage and grid management, particularly in regions with a high proportion of intermittent renewable sources such as solar and wind. In Latin America, where the energy matrix is already largely based on conventional hydropower, this technology can play a crucial role in advancing to a cleaner and more sustainable energy transition. PSH enable energy storage by pumping water from a lower reservoir to an upper reservoir during periods of low electricity demand (or excess generation, with low costs), allowing the stored water to later generate electricity during peak demand periods.

Globally, the total installed capacity through PSH reached 179 GW in 2023.

Below are some key aspects highlighting the potential of these plants in the region:

- Latin America has one of the most renewable energy matrices globally, with approximately 45% of its electricity generated from hydroelectric sources.
- Nevertheless, the growing integration of intermittent sources such as solar and wind power, requires effective storage solutions to ensure grid stability.
- PSHs are one of the most efficient, mature, and low-carbon forms of large-scale energy storage.
- The modernization of existing hydroelectric plants—many of which have been operating for decades—could offer an opportunity to incorporate pumping systems, enhancing their efficiency and storage capacity. This would extend the life of the facilities and play a key role in the integration of renewable energy in the region.

In terms of opportunities, PSH could be significantly accelerated if certain aspects are taken into account. First, geographical characteristics of many countries, which include coastal and mountainous cliffs. These natural features provide the elevation differences necessary for hydroelectric generation. In addition, the proximity to the sea in many countries offers access to water resources for collection and discharge, which could even provide desalination services. Third, an improved regulatory framework—particularly one that provides more accurate price signals—thereby enhancing the development of the technology.

4.1. Operation of reversible pumping plants

These plants operate using two water reservoirs situated at different altitudes. During periods of low energy demand, water is pumped from the lower reservoir up to the upper reservoir, storing potential energy for later use.

When energy demand rises, water is released from the upper reservoir back down to the lower reservoir, flowing through turbines that generate electricity.

This system enables excess energy to be stored and released when needed, functioning as a "giant water battery".

The amount of stored energy is proportional to the volume of water stored in the upper reservoir and the height difference between the reservoirs.

Storage systems can provide the valuable service of absorbing excess energy from the grid—A service that could even be financially compensated, especially if there is a negative price.

In addition to energy storage, reversible pumped storage plants can deliver a wide range of complementary services to the interconnected electricity system. These services help ensure a certain level of safety, quality and efficiency in the electricity supply—that include frequency regulation (primary, secondary, tertiary), voltage control through reagent supply and voltage regulation, rotation reserve, network inertia assurance, and Black-start capability, among others.

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4.2. Potential in Latin America and the Caribbean

The region's favorable geography with mountainous relief and abundant water resources facilitates the construction of reversible plants.

Countries such as Brazil, Chile, Mexico and Argentina are expanding their wind and solar capacities. Reversible power plants can help balance the intermittency of these resources.

This technology can help store energy during periods of high generation—such as daytime with solar energy—and release it at night or during periods of peak demand.

Unlike chemical batteries, reversible plants have a longer lifespan and lower environmental impact when they are well planned.

4.3. Challenges

The construction of reversible plants requires significant investments in infrastructure, which implies high initial costs.

New reservoir constructions can disrupt ecosystems and local communities, requiring rigorous environmental and social impact studies.

The lack of specific policies and remuneration mechanisms for energy storage poses a barrier to its implementation. Advancing regulatory and markets is therefore essential to support a development. An example is Brazil which has seen a massive advance of wind and photovoltaic energy recently—exceeding 70GW already in operation—there are still no PSH projects developed. Among the main barriers to the mass adoption of energy storage in Brazil are the lack of structured markets for ancillary services and the abundant water reservoirs of existing hydroelectric plants.

There are several reasons for the lack of development of PSH in LAC. One of the main factors is the presence of numerous hydroelectric power plants with large reservoirs that offer robust energy storage capacity. The region has developed numerous major hydropower plants in recent decades, with reservoirs capable of short-, medium- and long-term energy storage. Additionally, there is still significant remaining hydropower potential that could allow the construction of new hydropower plants at competitive costs, further enhancing additional storage to the systems. Furthermore, modernization projects could also extend the operational life of existing large-scale hydropower plants associated with these reservoirs. This would help power systems continue to benefit from their available storage capacity.

Second, the region lacks appropriate regulation for energy storage. Most energy systems do not exhibit price differences between peak and night prices. Furthermore, most regulatory frameworks do not include capacity payments, which are essential to make PSH projects economically viable. Additionally, markets for auxiliary or complementary services necessary for this type of project to be competitive, are non-existent.

Developers may be reluctant to invest or require a high return on investment to develop a project with high risk stemming from unclear regulation, uncertain revenue stream, and limited familiarity with the technology. Therefore, it is necessary to define a regulatory solution that makes PSH an attractive and viable investment option for most promoters. Nevertheless, the need for significant changes in the regulation of the electricity sector can pose a major barrier to the development of any storage project, including PSH. Therefore, it is recommended to first identify the least disruptive way to integrate storage into current network regulations, in order to accelerate its development.

Another barrier is the limited local experience and knowledge on energy storage. Although PSH is the only proven and by far the most widely adopted technology for large-scale energy storage worldwide, knowledge of its opportunities in the region is lower compared to other technologies, which limits its significant potential. PSH projects are not listed in public planning portfolios and there is a lack of widely available information regarding access to financing. Other energy projects—particularly renewables—are currently competing for funds that could be used to support the development of PSH projects.

Finally, potential barriers include social and political opposition, which resemble the challenges faced by newly constructed hydroelectric power plants. There is a challenge related to the insufficient involvement of stakeholders during the appropriate stages of the planning process. To mitigate these barriers, it is necessary to develop socially responsible projects. If not properly addressed, political acceptability can become a significant barrier to the development of the technology. Moreover, other storage technologies—that are perceived to have lower social and environmental impact—may be prioritized in planning processes.

4.4. Examples and projects in the region

Brazil: there are already some reversible plants, such as Pedreira (SP). Nevertheless, their current remaining facilities are focused on the control of flooding in rivers and maintaining water quality in metropolitan areas of major cities. Its use for power generation has declined over time. Brazil is examining the necessary adaptations in terms of regulation and commercialization to make new facilities viable.

Chile: With its vast solar potential in the Atacama Desert and strong wind potential in the south, is interested in developing reversible plants to balance its grid.

Mexico: The country is exploring storage options to support its expansion into renewable energy.

4.5. Future perspectives

With the advancement of renewable energy and the growing need for decarbonization, pumped storage plants are expected to attract increasing attention in Latin America

Regional cooperation and international financing can play a pivotal role in advancing projects, particularly in countries with lower investment capacity.

The integration of complementary technologies—such as batteries and green hydrogen—can further expand the potential of these plants.

In summary, pumped hydroelectric plants holds significant potential in Latin America to support the energy transition, providing stability and reliability in the power grid. However, fully realizing this potential will require overcoming a range of technical, economic and regulatory challenges.

5. Challenges

The challenges facing the advancement of hydroelectric projects in the LAC region can be grouped into two main categories: the need to advance in socio-environmental concerns and ensuring economic and financial viability, especially in times when the State investment is no longer as robust. Large hydroelectric projects in the region were often built in another context—Typically with minimal socio-environmental requirements and strong state involvement—Today, Nevertheless, it is necessary to propose solutions to address these challenges.

5.1 Environmental and Social sustainability

It is important to identify and study successful constructions and operational periods to learn from the best practices in our region

One proven protocol worth following is the Hydropower Sustainability Standard [8], a comprehensive assessment and certification framework that ensures accountability in the development of hydropower. It provides a clear roadmap to harness the potential of hydropower in a way to deliver a positive impact that benefits communities and our environment. The Standard promotes the responsible development of this essential energy source, ensuring that progress is aligned with environmental protection.

Eight hydroelectric plants are currently in different phases of protocol implementation that could help future development:

- Chaglla Hydroelectric Power Plant of 456MW in Peru.
- Chorreritas Hydropower Project of 19.9MW in Colombia.
- Ituango Hydroelectric Project of 2,400MW in Colombia
- Jirau Hydropower Plant of 3,750MW in Brazil
- Mascarenhas Hydropower Plant of 198MW in Brazil
- Reventazón Hydroelectric Power Project of 306MW in Costa Rica
- Santo Antônio Hydroelectric Power Plant of 3.568MW in Brazil
- São Simão Hydroelectric Power Plant of 1.710MW in Brazil

Finally, it is important to highlight all involving parties concerned from the initial stages of project planning. For example, Brazil requires a strategic environmental assessment from the initial stages of the inventory phase of a river basin’s hydroelectric potential.

5.2 Investments in Hydropower

Policy measures that offer clearer assurances about future revenues can reduce investment risks and ensure the economic viability of hydropower projects. Since the 1950s, over 90% of hydropower plants have been developed under conditions that ensure revenue certainty through power purchase guarantees or long-term contracts. This has occurred in both vertically integrated and liberalized electricity markets. Nowadays, difficulties related to complex permitting procedures, environmental and social acceptance, and long construction timelines can contribute to higher investment risks. In advanced economies, the economic viability of hydropower plants has declined due to the decreasing electricity prices and a lack of long-term income certainty. Long-term revenue visibility—especially for large-scale hydropower projects with long developed timelines—significantly reduces financing costs and enhances project viability, thereby encouraging investment. This is particularly important when the private sector is involved. [9]

Nevertheless, as previously mentioned, the current operational reality of electricity systems—equipped with variable dispatch source—lacks controllable generation. Thereby, in this context of decarbonization, hydroelectric plants must be reconfigured to serve as an effective solution.

To achieve this, it is essential to revise the regulatory framework for remuneration of hydroelectric power plants in several countries. These revisions should enable remuneration not only for base energy, but also for the flexibility of other services provided by hydroelectric plants.

6 Conclusions

Hydropower stands as a cornerstone in the transition to a cleaner and more resilient energy future, especially in Latin America and the Caribbean—a region endowed with vast water potential. Nevertheless, realizing its full potential demands an immediate and collective commitment to maximize their positive impact.

With the global need to double installed hydropower capacity by 2050, the region faces a historic opportunity to lead this effort. Investments in modernization, hydraulic storage, and new technologies can enhance energy security while reinforcing the capacity to confront climate and socioeconomic challenges that affect our communities.

Now is the time for governments, institutions and the private sector to prioritize hydroelectricity as a strategic pillar. It represents far more than just energy—it is a legacy that we will leave to future generations—. With vision and decisive action, we can turn today's challenges into tomorrow's opportunities, and together we can forge a more sustainable, equitable, and prosperous future for all.

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