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Hydropower Development in Three South American Countries: Brazil, Colombia, and Ecuador

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ABSTRACT

The present manuscript aims to identify the advantages and consequences of hydropower development, showing a view of trends finding the status and situation in Brazil, Colombia, and Ecuador. This study uses a non-experimental methodology based on a comprehensive literature review of relevant papers retrieved from 41 selected papers that are summarized covering different application areas in these selected countries. In addition, the non-experimental methodology is guided by a perspective design sequential with a qualitative phase defining two indicators that do a relation between the people and the installed capacity in megawatts (MW) and energy production in gigawatts hour (GWh). The results show Colombia has the main installed capacity and energy generation per capita, followed by Ecuador, and finally, Brazil. According to the models and studies, the general hydropower potential of Brazil, Colombia, and Ecuador decreases as time goes on because this renewable energy affects the water quality, interacting deeply with the surrounding environment. However, in South American countries only 34% of hydropower potential has developed.

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INTRODUCTION

Approximately 180 countries realized economic benefits from hydropower by 2020. Today's technology is widely used for hydropower generation [1]. In addition, hydropower produces electricity at a cost-competitive rate of the 2-5 ¢/kilowatt-hour as coal and gas [2, 3].

As of 2019, the International Hydropower Association (IHA) reported global hydropower capacity at 8988 megawatts (MW), which accounted for 89 percent of the world's hydropower capacity [4]. Furthermore, Our World's Information in Data means that hydropower in 2019 covers around 6.4% of global primary energy, followed by wind 2.2%, solar 1.1%, biofuels 0.7%, and others with 0.9% [5, 6]. Figure 1 represents the global energy consumption by source in terawatt-hours (TWh) in the last 55 years, and hydropower is the principal renewable in the energy grid.

Figure 1 demonstrates various sources of energy such as oil, coal, gas and renewable energy. Still, the renewables such as hydropower, wind, and solar with respect to time had a conservative growth, demonstrating the feasibly of developing renewable projects around the world. There has been considerable progress in hydropower since it first became a source of industrial power in the past 55 years [7, 8].

Although this information is accurate, there is still an opportunity for considerable increases in hydropower capacity in long term (2050); this includes a scenario for production of over 8,000 TWh [9]. Otherwise, according to the World Atlas, the hydropower potential shows that South America has about 30% of the worldwide potential [10].

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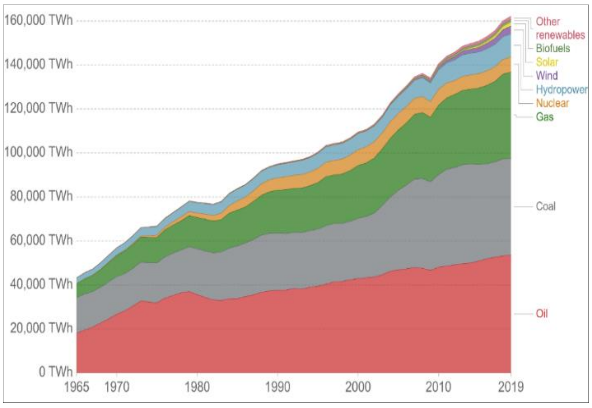

Figure 1. Global energy consumption in TWh [6]

Based on data published by the International Hydropower Association in 2021, only this renewable source produced 4,379 TWh as the highest contribution ever generated by a renewable power source [11]. As for hydroelectricity, the International Energy Agency (IEA) projects that it continues to be the main source of energy, but the share will drop below 50% for the first time in 2024 because it will combine wind, and solar generation to almost double to slightly above 4,000 TWh over the forecast period [12].

However, little is known about their impacts despite their renewable nature. Due to its use and lack of economic feasibility, hydropower has negative social and environmental effects [13]. It is a renewable source with a robust contact with the near location [14, 15]. As a result, the hydropower sector needs to ensure sustainable growth [16].

Therefore, to know the advantages, and disadvantages of hydropower, it analyzes three countries in South America: Brazil, Colombia, and Ecuador, with similar climate conditions, related ecosystems, comparable social populations, and closeness. Moreover, Figure 2 illustrates the map of selected countries that they presented the most of data and studies conducted about hydropower development in the region.

Hence, the study will show how the struggle among sustainability and development impacts the feasibility of hydropower production where political choice and a deficiency of methodical sustenance prevail in the socio-environmental study with resource consciousness.

In general, hydropower projects receive much criticism due to their associated environmental and social impacts because they do not only affect regional areas but sometimes even cross-national boundaries [17, 18]. According to the Regional Energy Integration Commission of South America, the average hydropower developments in Brazil, Colombia, and Ecuador are only 59%, 13%, and 22%, respectively [19].

Around the background, while this manuscript preset a novelty context around the hydropower development and its benefits and impacts on three countries with significant potential in this renewable, the scientific innovation of the document has discussed the opening of confronting hydropower as the most widely used renewable energy globally to discuss improvement plans for the future large-scale hydroelectric project's construction. In addition, it calculates some indicators of Brazil, Colombia and Ecuador since each population gives a different perspective of the deployment of this renewable energy source.

This study aims to identify the advantages and consequences of hydropower development, showing a view of trends finding the status and situation in Brazil, Colombia, and Ecuador.

MATERIAL AND METHODS

This study uses a non-experimental methodology based on a comprehensive literature review of relevant papers with key words, besides the figure of the three countries analyzed in this manuscript.

After the final screening, 134 publications, including journal articles, conference papers, books, and online reports, were selected. Throughout these documents, 41 selected papers are summarized, covering different application areas and the sustainability of hydropower projects in these three countries. Research on risk assessment of hydropower projects is relatively rare in Brazil, Ecuador, and Colombia, so researchers are frequently cited more than once.

Additionally, it collects data from the Ministry of Energy of each country. In addition, the non-experimental methodology is guided by a perspective design sequential with a qualitative phase.

In the quantitative phase, data on installed hydropower capacity and supplied energy versus the population of Brazil, Colombia, and Ecuador were crucial in defining indicators. Therefore, it defines two

Figure 2. Analyzed countries (Ecuador, Brazil and Colombia) [20]

indicators that do a relation between the people and the installed capacity in megawatts (MW) and energy production in gigawatts hour (GWh) to generate comparisons, as expressed in Equations (1) and (2).

$$MW\ per\ capita = \frac{Population\ per\ country}{Hydropower\ capacity} \tag{1}$$

$$GWh\ per\ capita = \frac{Population\ per\ country}{Hydropower\ generation} \tag{2}$$

The researcher's criteria defined these two indicators to discover concepts and compare the capacity and generation of the population. Brazil, Colombia, and Ecuador are the chosen states because these countries have similar social conditions and people with identical characteristics and closeness; these nations are analyzed from socio-economic statistical data and technical information.

RESULTS AND DISCUSSION

First, the country's context is defined by the Gross Domestic Product (GDP) per capita, for the collected data from 2010 to 2020; the GDP is shown in Figure 3.

As demonstrated in Figure 3, in the three countries selected, the GDP per capita had variations with respect to time. Still, in the last 20 years, reasons such as the scale economies and the pandemic Covid-19 since November 2019 affected and slowed down the markets. Moreover, the results show that Brazil is the top country on monetary indicators around the GDP representing the capacity to quickly develop more infrastructure, such as hydropower projects, followed by Ecuador and Colombia.

Data from British Petroleum allows the development of the context of these countries' energy grids. Figure 4 illustrates the per capita primary energy consumption by source in 2019.

As illustrated in Figure 4, which shows the kilowatt-hour (kWh) tendency used up by a person in 2019, the hydropower consumption source in Brazil has 31%, besides Ecuador with 30% and Colombia with 24%;

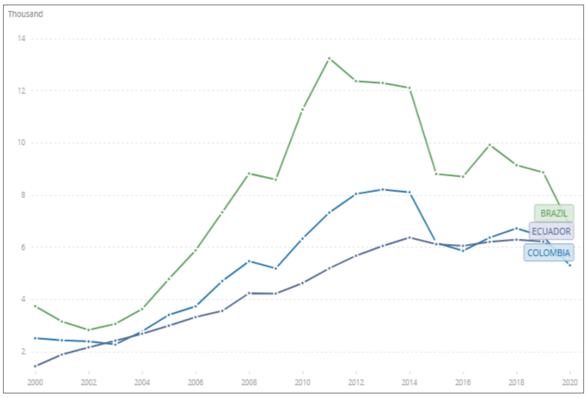

Figure 3. GDP per capital three countries 2000 - 2020 [21]

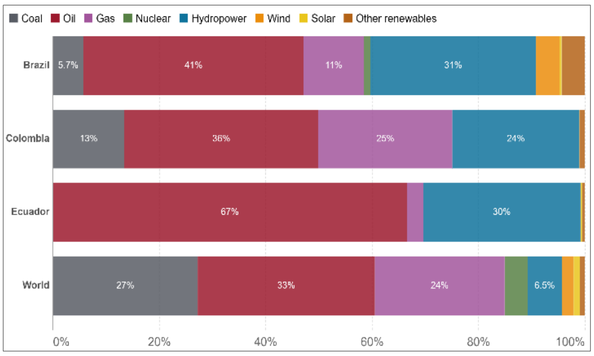

Figure 4. Energy consumption by source 2019 [5]

finally, the global average of hydropower use is 6.5% [5]. This tendency of energy consumption is similar to the GDP per capita indicators by country as illustrated in Figure 3.

On the one hand, the International Hydropower Association data shows the capacity and energy generation by the country for the year 2020. In addition, it took the population data of the World Bank for the same year. Therefore, Tables 1 and 2 show the installed capacity and energy generation indicators defined in Equations (1) and (2).

As Table 1 and 2 showed, the relation between the installed capacity and the generation is variable. It illustrates how much energy and ability each country has by hydropower consumption, giving Colombia a significant indicator, followed by Ecuador and Brazil. However, Brazil has the most considerable hydropower installed capacity. Nevertheless, with fewer established capacity indicators, the relation between population and power reduced the calculation.

Table 1. Hydropower installed capacity indicator (MW per capita)

No.	Country	Hydropower capacity [MW][a]	Population[b]	MW per capita
1	Brazil	109,271	211,049,527	1,931
2	Colombia	11,941	50,339,443	4,216
3	Ecuador	5,076	17,373,662	3,423

Sources: a. [11], b. [22]

Table 2. Hydropower energy generation indicator (GWh per capita)

No.	Country	Hydropower generation [GWh][a]	Population[b]	GWh per capita
1	Brazil	409,550	211,049,527	515
2	Colombia	45,820	50,339,443	1,099
3	Ecuador	24,799	17,373,662	701

Sources: a. [11], b. [22]

In contrast, it has the same tendency by country in the energy generation indicator. Both calculated indicators show the relation of the population and the hydropower development by the government; the results show Colombia has the main installed capacity per capita and energy generation per capita.

On the other hand, according to the South American countries, the energy and climate policy is profoundly implanted inside many targets. They are heavily dependent on extractive industry exports with high levels of financial inequality and depend on export revenues from the extractive industry [23].

The International Hydropower Association references that the ten countries will have 176 GW of hydro installed capacity in 2020, as shown in Table 3 [24]. Brazil is the top country that alone accounts for 109 GW of potential expansion, with around 40 hydropower projects underway [24, 25].

There is considerable potential for future advancement in Argentina, Colombia, and Peru. There are numerous projects recognized within the brief term. Still, the pandemic Covid-19 breaks the vitality planning, as shown in Table 3.

On the other hand, the Regional Energy Integration Commission of South America says that the current hydropower capacity has the projection in Table 3 [19].

Averaging hydropower development in Brazil, Colombia, and Ecuador (59% + 13% + 22%) has 31% of feasibility executed in the context that South American countries have the 34% developed. There is a way to set this renewable source [19].

Brazil

Considering that Brazil has a very large hydropower sector for its electricity, it has produced about 75% of the country's energy in the last decade on average, and has 109 GW of installed capacity [4, 26].

Brazil's principal advantage is that hydropower provides a constant response from nature-free [27]. Hydropower may also act as an adjunct to variable other renewable sources (wind, solar), supporting their growth and satisfying demand when these sources are unavailable [28].

Based on the reference, an analysis of hydropower alternatives was done. So as to achieve its goal, the Brazilian government plans to invest in 26 large hydropower and water treatment projects in the Amazon rivers with a capacity of 44 GW to be installed on a reservoir area of approximately 9,000 square kilometers and which are set to be undertaken at an investment of US$ 50-70 billion [29].

Hence, alternative energy sources rather than hydroelectric dams and reservoirs can avoid the adverse effects on the environment and society from hydropower dams [30]. As a pre-condition, it is essential to separate the oil use from the other renewable energy sources that can also replace large hydro plants which damage the environment [31].

Even though the various analyses conducted in Brazil show different outcomes, the projected results show that if there are no climate adaptation policies and mitigation policies in place in 2050, the hydropower would be reduced and pollutants would be increased [32]. In addition, by 2050, emissions rise from a series of 2911–4274 TCO_2eq/year of the reference scenario to a range of 2920–4280 TCO_2eq/year for the low scenario and 2964–4318 TCO_2eq/year for the high influence scenario, changing between 1% and 2% of TCO_2eq, respectively on affections [32].

Table 3. South America hydropower feasibility and installed capacity in 2020

No.	Country	Inventory [GW]	Installed [GW]	Development [%]
1	Argentine	45	11.34	25%
2	Bolivia	40	0.73	2%
3	Brazil	185	109.27	59%
4	Chile	25	6.95	27%
5	Colombia	93	11.94	13%
6	Ecuador	23	5.1	22%
7	Paraguay	13	8.8	68%
8	Peru	62	5.39	9%
9	Uruguay	2	1.53	75%
10	Venezuela	28	15.3	55%
Average				34.1%

Source: [19]

Colombia

The Colombian electricity sector is currently dominated by hydropower in renewables. During the last decade, it has remained the leading, comprising 76% of total electricity generation to sustain a growing population [33]. According to the government, investing in hydropower generates new jobs, and offers an economic products sphere generating an economic circle of jobs and services for the society [34].

The International Renewable Energy Agency mentions that Colombia consumed 70,203 GWh of energy in 2019 [35]. Moreover, it conducted a multimode analysis of climate change and hydroelectricity, determining that water accessibility is variated in some areas; thus, hydropower production fluctuates as a result.

In Colombia, there are medium to large hydropower plants with an adequate installed capacity of more than 100 MW connected to the National System; the total number of power plants includes 19 in the entire territory. On the other hand, the hydropower installed capacity represented 11,941 MW in 2020, and with this capacity, the nowadays reduction of CO_2 is 31.52 Tg.CO_2eq/year [35].

Four independently developed energy models are used in this research, two of which are partial equilibrium models, and two are general equilibrium models, to determine the extent of hydropower degradation for the next 30 years and to determine the need for other technologies developed in addition to those used to mitigate the damages caused by climate change in hydropower [36].

Furthermore, according to another study, during the 2015 to 2029 period, the hydropower production capacity in Colombia would decrease by 5.5–17.1% due to climate change if an increase in temperature and precipitation was simulated at 0.5 °C [37].

Therefore, Colombia has adopted a new energy policy that aims to expand renewable energies and reduce barriers and is analyzing support and incentive programs, including reducing taxes to implement new renewable energy projects [36].

Additionally, new non-hydropower projects are recommended to sustain a growing population. Among other factors, the change in Colombia's electrical source will be determined by the economy, the financial sector, the market for productive products, and the difficult or uncertain regulations for global energy models [33].

The future hydropower projects for Colombia need to explore energy synergies between alternative expansion routes with other renewables and possible social and environmental effects in other sectors [38].

Ecuador

In Ecuador eight hydropower projects cost nearly USD 6 billion between 2007 and 2015, which led to the country doubling its electricity production capacity [39]. International Hydropower Association data shows that Ecuador's hydropower capacity grew by 1.3 percent in 2016, behind only China and Brazil [37].

In Ecuador the hydropower has a fundamental role in energy policy to achieve the objectives of reducing greenhouse gas emissions, but long-term climate changes affect the protagonist of these plants in energy production favor. For example, for the country, currently with the construction of the last hydroelectric projects has an installed capacity of 5076 MW (2019), controlled CO_2 emissions are 13.4 Tg.CO_2eq/year [40].

In this regard, Ecuador evaluates the long-term needs for hydropower in Ecuador's energy system and the contribution it makes towards fulfilling the Nationally Determined Contributions (NDC) for 2015-2022. Hydropower has been shown in studies to be a stressor on water resources due to environmental conditions, such as water storage and hydrological changes induced by dams, moreover and lands may be flooded from the water bypassed [41].

There is uncertainty regarding hydropower in Ecuador. Its total electricity supply will vary significantly from 53% to 81% by 2050; meaning that it will not have to deploy an extensive hydropower infrastructure to achieve Ecuador's NDC. Still, it will instead have a more diversified portfolio of energy sources, including renewable energy [41].

In addition, another study of Ecuador's Land Use and Energy Network Analysis model of six basins that contain most hydropower projects (10) determines impacts of climate change quantified for the period 2071-2100 compared to 1971-2000 through modeling and simulations framework on six different scenarios. The top results show hydropower production will vary between – 55% and + 39% of the average historical set, which means heavy reductions in hydroelectricity [42].

Regulatory, financial, and social issues face the hydropower deployment in Ecuador, highlighting the importance of conducting a comprehensive energy system analysis [43]. Ecuador found the advantage of developing hydropower projects with the natural conditions on their rivers, but the aggressive distribution causes social, cultural, and environmental impacts to transform the energy grid [44].

Discussion

Latin America relies largely on hydropower for more than half of their electricity, making it one of the greenest electrical grids on Earth. From the 19th century onwards, there was a rise in the establishment of electrical companies in Latin America due to the vast hydropower potential in the region[45, 46]. Future hydroelectric development is not without challenges. It is crucial to identify, mitigate, and manage the effects of natural overexploitation, such as the dam's development to minimize their environmental and social impacts in the upcoming [47].

Table 3 summarized the average hydropower feasibility executed in Brazil, Colombia, and Ecuador is 31%. In spite of this, this new progress does not appear to be developing within a framework of political ecology that includes social, environmental, and ecosystem protection, as well as constructive transparency [48].

On the one hand, Briones et al. [49] and Naranjo-Silva et al. [50] studies questioned the role and palpable profits of hydropower in the electricity generation sector since there are an increasing arrangements number for power generation, such as improved access to electricity, economic development, flood control, which reduces carbon emissions, etc. Nevertheless, these effects tend to be circumscribed, and only occur in the isolated urban areas, where the population has difficulty accepting [51]. Consequently, it is evident that hydropower will remain a debatable source of renewable energy in the future as well; for that reason, it is required to evaluate the risks, benefits, viability, size, and costs associated with this source of energy in the near future [52].

Thus, comparing the results of Brazil, Colombia, and Ecuador, for example, Chile verified impacts covered per megawatt produced by small hydropower internationally because they are developing in mountainous regions, causing reservoirs in basins around the world [53]. Nevertheless, it is important to accentuate that the conservation principle of these structures is based on the views of the affected populations from an ethnographic or collaborative perspective. Hydropower is an important aspect of the environmental laws, as it is said that they evaluate hydropower integrated with other ecological issues. It is recommended that dams be better regulated [53, 54].

Comparing, several studies have been conducted in the United States of America to establish that future climate change on water availability can be determined based on the seasonal variation among climate models, air currents, and the water inputs when producing hydropower. Climate change and its effects on the hydrological and natural water cycles make climate change a significantly critical threat to the future [55]. Forecasts for federal projects call for a decrease of 2 TWh in an annual generation [56]; hence, similar studies and projections of Brazil, Colombia, and Ecuador that estimate temperature and precipitation changes will reduce the hydropower generation.

On the other hand, regardless of the development approach, the fast changes respond to the growing population demands for energy [57]. The different hydropower analyses have limitations and complex interactions of impacts on social, environmental, and economic parameters, and these effects are poorly quantified. It is estimated at approximately one trillion dollars to offset the last eighteen years of hydropower production triggered by climate change [58, 59].

The speed of technological progress explains the need for countries such as Brazil, Colombia, and Ecuador to propose different options as sources of electricity generation. The results obtained from a general comparison in this manuscript contribute to future decision-making about the most appropriate implementation for each country. Furthermore, the Latin American electricity sector requires new technologies, sources, and potential alternatives for energy generation because it is based mostly on cost reduction but also on contribution to the environment and surroundings as an essential mix to advance in challenges such as population energy demand, high reliance on fossil fuels, and climate change.

In order to drive the economic and industrial growth of any developing nation, hydropower is one of the most important infrastructures. In Nigeria, a study calls for the development of pumped water systems so that the tailwater can be reused, particularly during periods of small or no rainfall and low inflow; the results mention that there is about 25% variability in the amount of hydropower generated that is unaccounted for by the climatic and hydrological variables used when designing the projects [60].

On the other hand, Ethiopia mentions that the development of hydropower projects is inevitable. Hydroelectric energy technology can contribute to small measures to improve the electricity supply in rural communities. This is because the electrical energy needs of these communities are modest and their contribution would be greatly appreciated [61].

Despite the study generated with these three countries, it is important to mention that the scope is reduced because it only takes information from Brazil, Colombia and Ecuador, leaving aside other countries worldwide with a great development of this renewable source to generate indicators, comparisons and know the advantages and disadvantages of hydropower development throughout the different regions.

CONCLUSIONS

The development of hydropower potential in 2020 at Brazil, Colombia, and Ecuador is 59%, 13%, and 22%, respectively. Nowadays, the average feasibility executed in South American countries is only 34%.

According to the models and studies, the hydropower potential of Brazil, Colombia, and Ecuador decreases as time goes on because this renewable energy affects the water quality, and interacting deeply with the surrounding environment. Climate policy progress and a low carbon strategy based on renewables are required through cooperation instruments to have plans and projects of sustainable criteria.

Both calculated indicators show the relation of the population and the hydropower development by country; the results show Colombia has the main installed capacity and energy generation per capita, followed by Ecuador, and finally, Brazil presenting the subsequent calculous: 4,216/1,099 - 3,423/701 - 1,931/515 (MW per capita/ GWh per capita), respectively.

It is recommended to develop energy studies in forecasting scenarios with renewable sources, where energy diversification considers the climate variations that affect hydropower. Future directions may include creating a map that identifies overused hydrographic basins to develop resilient hydropower projects in areas with the lowest ecological impact due to outside probable for damage.

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CONFLICTS OF INTEREST

All the authors declare no conflict of interest.

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Persian Abstract

چکیده

هدف این مقاله شناسایی مزایا و پیامدهای توسعه نیروگاه‌های آبی، نشان دادن نمایی از روند یافتن وضعیت و موقعیت در برزیل، کلمبیا و اکوادور است. این مطالعه از یک روش غیرتجربی مبتنی بر بررسی ادبیات جامع مقالات مرتبط بازیابی شده از ۴۱ مقاله انتخاب شده استفاده می‌کند که به طور خلاصه حوزه‌های کاربردی مختلف در این کشورهای انتخاب شده را پوشش می‌دهد. علاوه بر این، روش غیرتجربی توسط یک طراحی چشم‌انداز متوالی با یک فاز کیفی که دو شاخص را تعریف می‌کند هدایت می‌شود که رابطه بین افراد و ظرفیت نصب‌شده در مگاوات (MW) و تولید انرژی در گیگاوات ساعت (GWh) را ایجاد می‌کند. نتایج نشان می‌دهد که کلمبیا دارای ظرفیت نصب شده اصلی و سرانه تولید انرژی است و پس از آن اکوادور و در نهایت برزیل قرار دارند. با توجه به مدل‌ها و مطالعات، پتانسیل عمومی انرژی آبی برزیل، کلمبیا و اکوادور با گذشت زمان کاهش می‌یابد زیرا این انرژی تجدیدپذیر بر کیفیت آب تأثیر می‌گذارد و عمیقاً با محیط اطراف تعامل دارد. با این حال در کشورهای آمریکای جنوبی تنها ۳۴ درصد از پتانسیل انرژی آبی توسعه یافته است.