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Hydropower Development in Ethiopia, Tanzania, Zambia, and Zimbabwe: A Comprehensive Review

Una revisión del desarrollo de la hidroelectricidad en Etiopía, Tanzania, Zambia y Zimbabue

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Abstract

All continents are currently undergoing energy transitions toward low-carbon economies driven by renewable technologies. Africa is no exception; with its rapidly growing population and expanding economy, it represents nearly one-fifth of the global demographic. Although the African continent contributes less than 3% of global carbon emissions, it is already experiencing severe and disproportionate impacts from climate change. This manuscript aims to analyze the hydropower development in Ethiopia, Tanzania, Zambia, and Zimbabwe, with the objective of assessing the current use and projected role of this renewable resource. These countries were selected for their significant hydroelectric potential and ongoing investment in renewable energy infrastructure. While these nations have made substantial commitments to hydropower, climate-induced shifts in hydrological patterns, particularly increased drought risk, pose serious challenges to energy security and sustainability. Consequently, electric utilities must not only project future energy generation but also implement robust mitigation and adaptation strategies to safeguard long-term investments. Given the critical role of climate change as an external variable influencing energy planning, it is essential to evaluate hydropower and reservoir operations through a multidimensional lens encompassing parameters such as temperature, precipitation, humidity, river flow, watershed characteristics, and related factors.

Keywords: Africa; energy; hydroelectric; projections; sustainable.

Resumen

Todos los continentes están atravesando actualmente transiciones energéticas hacia una economía baja en carbono desde las renovables. Uno de estos continentes es África, donde la población y el crecimiento económico impulsan una quinta parte del mundo. Si bien el continente africano tiene la menor responsabilidad por el calentamiento global, con menos del 3% de las emisiones, ya enfrenta severos impactos del cambio climático. Por lo tanto, este manuscrito tiene como objetivo analizar el desarrollo de hidroeléctrico en Etiopía, Tanzania, Zambia y Zimbabwe para conocer el uso de esta renovable y sus proyecciones. Estos países fueron seleccionados de acuerdo con información que tienen una amplia proyección hidroeléctrica. En estos países se ha invertido una cantidad valiosa en hidroelectricidad, pero, el impacto del cambio climático aumenta el riesgo de sequías, lo que preocupa debido a una variación en los patrones. Las compañías eléctricas no solo necesitan pronosticar la generación futura de energía, sino que también tomar medidas de mitigación y adaptación para mantener sus inversiones. Además, el cambio climático es un parámetro externo que juega un papel importante al proporcionar datos de referencia para futuros proyectos, siendo necesario evaluar las operaciones de energía hidroeléctrica y embalses bajo un conjunto de parámetros (temperatura, precipitación, humedad, caudal de ríos, cuencas y otros).

Palabras clave: África; energía; hidroeléctrica; proyecciones; sostenible.

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1. Introduction

Globally, renewable-based electric power systems have played an increasingly critical role in improving energy access, particularly in rural and remote regions where electricity availability remains limited. According to the Global Status Report of Renewables, global investment in renewable energy capacity increased by 2% in 2020, demonstrating resilience amid the economic disruptions caused by the COVID-19 pandemic. Distributed renewable energy systems have continued to expand access, contributing up to 10% of electricity generation in some countries [1].

In 2020, global investment in renewable power and fuels, excluding hydropower projects larger than 50 MW, totaled USD 303.5 billion. For the sixth consecutive year, developing and emerging economies surpassed developed countries in renewable energy capacity investment, reaching a combined total of USD 153.4 billion. That same year, funding in developed economies increased by 13%, while investment in emerging markets declined by 7%, reflecting broader trends in global renewable energy financing, excluding large-scale hydropower projects [2, 3].

Focusing specifically on hydropower, which remains the leading source among renewable technologies, the International Hydropower Association (IHA) reported that global hydropower generation reached an estimated 4,252 TWh in 2021, following a 1.9% increase in 2020. Despite the disruptive effects of the pandemic-induced recession, which impacted many of the world's major hydropower technology providers, the global hydropower market continued to grow. Notably, China accounted for more than half of all new capacity additions in 2021, contributing an increase of 20,840 MW [4].

However, renewable energy use is increasing across all economic sectors, reflecting a growing reliance on electricity to meet societal and industrial demands. According to the REN21 Group, much of the recent progress in expanding the share of renewables in global electricity production has resulted in renewables contributing nearly one-third (30%) of total electricity generation in 2022 [5], as shown in Figure 1.

Figure 1 illustrates that hydropower remains a leading source among renewable energy technologies, and that the industry is expected to face both challenges and opportunities in the years to come. These challenges include operational and technical constraints, environmental and social acceptance issues, declining global wholesale electricity prices, and adverse climate impacts, all of which directly affect hydropower generation [5, 6].

Investing in hydropower development offers substantial economic benefits by accelerating growth and contributing to the reduction of greenhouse gas emissions. Hydropower plays a critical role in advancing clean energy technologies within national economies, which is why this paper examines the current status and future potential of hydropower in selected African countries [7].

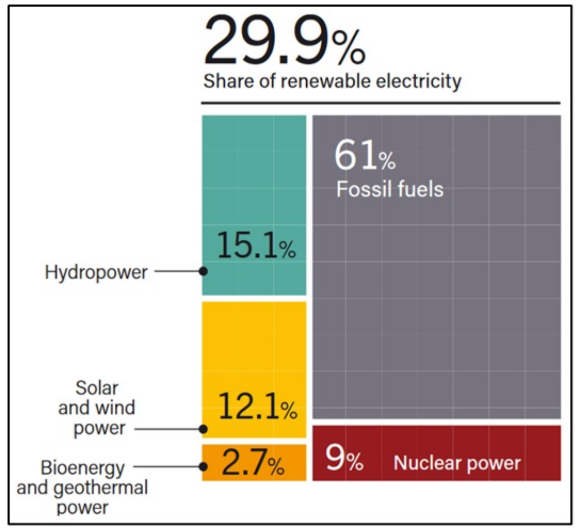

Figure 1. Global energy grid composition [8], p. 1

Currently, approximately 40% of the population in Africa lacks access to electricity, with the majority of those affected living in sub-Saharan Africa. Countries such as Ghana, Kenya, and Rwanda are on track to achieve universal electricity access by 2030, serving as examples for others to follow. Africa also has the lowest per capita consumption of modern energy in the world, particularly from renewable sources. As population and income levels continue to rise, demand for modern energy is expected to increase by one-third between 2020 and 2030, according to the Sustainable Africa Scenario. In parallel, several African countries have committed to reducing emissions by approximately 550 Mt.CO2 by 2030, equivalent to 40% of the continent's current emissions [9, 10].

In Africa, hydropower currently accounts for approximately 17% of total electricity generation. In some countries, including the Democratic Republic of Congo, Ethiopia, Malawi, Mozambique, Uganda, and Zambia, hydropower supplies as much as 80% of total energy consumption [11]. According to the World Bank, Africa's installed hydropower capacity is expected to reach approximately 40 gigawatts (GW) by 2030 [12]. However, nearly 25% of existing plants are not operational due to inadequate maintenance and poor infrastructure. Additionally, the International Hydropower Association (IHA) estimates that the continent has a development pipeline of 117 GW and a remaining hydropower potential of 478 GW [13].

According to data from organizations involved in collecting information on renewable energy, particularly hydroelectricity, this energy source is generally perceived positively due to its reliance on non-depleting natural resources. However, hydropower also entails environmental and social impacts that must be carefully considered. This manuscript aims to analyze hydropower development in Ethiopia, Tanzania, Zambia, and Zimbabwe (Figure 2), focusing on its current use and future projections through a comprehensive review of relevant documents and energy sector policies. These countries were selected based on the available data indicating their significant hydroelectric potential. Additionally, multiple investigative sources were consulted to support and consolidate the information presented in this review.

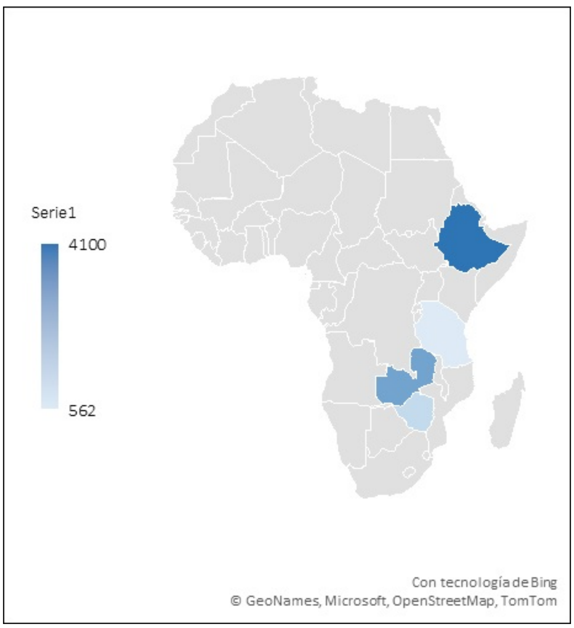

Figure 2. Countries selected for this study [14]

2. Materials and Methods

To analyze hydropower development in Ethiopia, Tanzania, Zambia, and Zimbabwe, the methodology begins with a comprehensive review of literature and documents, guided by an investigative approach. This first step involves collecting relevant sources, including scientific studies, government reports, and energy and environmental policy documents specific to the selected countries. The review focuses on studies that address both hydropower development and climate change impacts in the region, with an emphasis on recent publications, preferably from the past five years, to ensure relevance and timeliness. Priority is given to reliable sources, including academic databases, reports from international organizations, and official government documents.

The second step of the methodology involves a detailed analysis of each country's energy policies and regulatory frameworks. This analysis aims to assess how national policies support hydropower development by identifying key environmental regulations, government incentives, and climate change adaptation strategies. A comparative analysis is then conducted to examine similarities and differences in how climate considerations are integrated into national energy policies, which is essential for understanding the broader context in which hydropower projects are being developed.

The third step involves assessing major hydropower projects in the selected countries. This analysis includes the collection of data on each project's installed capacity, technological configuration, annual energy production, and future generation projections. Additionally, the efficiency and sustainability of these projects are evaluated, considering their vulnerability to climate variability, including droughts and shifts in precipitation patterns, which are becoming increasingly frequent due to climate change.

The fourth step of the methodology involves a comparative case study of the four selected countries, presented in the discussion section. This approach facilitates the assessment of each country's challenges and achievements in developing hydropower under changing climate conditions. Both qualitative and quantitative methods are employed to analyze national experiences, with a particular focus on best practices and lessons learned.

Overall, this article outlines the methodology used to select and analyze scientific documents, providing a detailed account of the keywords applied: "African hydropower development," "Hydropower development in Ethiopia, Tanzania, Zambia, and Zimbabwe," and "Energy matrix in Ethiopia, Tanzania, Zambia, and Zimbabwe." It also specifies the search strings employed, the specific databases and digital libraries consulted, including SCOPUS, Web of Science, and other sources relevant to hydropower research, as well as the time frame of the literature review, which spans from 2017 to 2024.

Finally, the results will be discussed, as validation is essential to ensure the reliability and relevance of the study's conclusions. The combination of these methodological steps provides a comprehensive and rigorous basis for analyzing the current state and future prospects of hydropower in these African countries, within the broader context of accelerating climate change.

3. Results and discussion

According to data from British Petroleum, hydropower generation by continent in 2021 shows that Asia produced the largest share, generating 2,176 TWh. This upward trend has continued since 2003. In comparison, the Americas generated 1,239 TWh, Europe produced 659 TWh, and Africa generated only 146 TWh, indicating significantly lower output. When comparing

Africa's generation to that of Asia [15], the continent accounted for just 7% of Asia's hydropower production, confirming Africa as the region with the lowest level of hydropower development in 2021 [16]. As shown in Figure 3, global hydropower development in 2021 is represented by total installed capacity across regions.

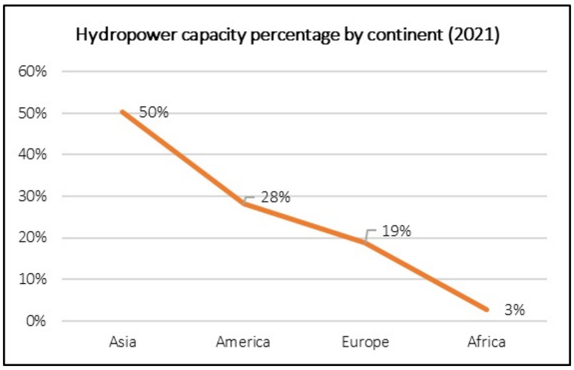

Figure 3. Global hydropower installed capacity by continent in 2021

As shown in Figure 3, hydropower installed capacity in 2021 varied significantly across continents, with Asia leading with 655 MW, followed by the Americas with 382 MW, Europe with 254 MW, and Africa with only 38 MW. These figures reveal substantial disparities in hydropower development, particularly in regions with limited energy infrastructure. Africa presents considerable opportunities for expanding this key renewable energy source [15], [17]. Additionally, the study includes a figure that displays the top 18 African countries by hydropower installed capacity, including pumped storage, as well as the countries selected for this review.

As shown in Figures 3 and 4, hydropower development varies significantly across continents and among African countries. Based on these disparities, this study focuses on Ethiopia, Tanzania, Zambia, and Zimbabwe, selected for their considerable hydroelectric development potential and projected growth. To support this analysis, several investigative sources were reviewed to consolidate relevant information and assess the current state and projected use of hydropower in the selected countries.

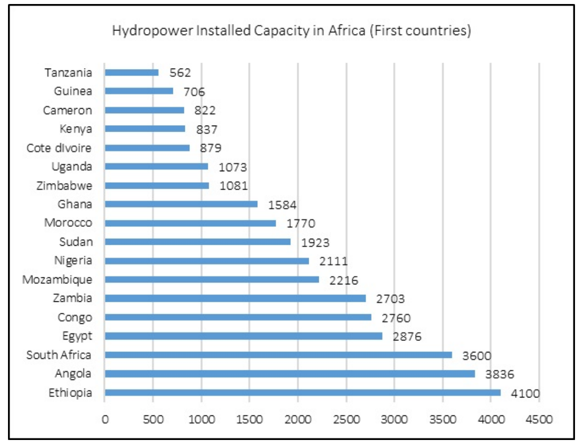

Figure 4. Hydropower installed capacity in Africa [4]

Ethiopia

Ethiopia is a developing country endowed with abundant water resources. Consequently, its hydropower production capacity increased from 850 MW in 2010 to 4,100 MW in 2021. The government is currently undertaking several major hydropower projects aimed at positioning Ethiopia as a key power hub in East Africa. Notable among these projects are the Gibe III Hydropower Plant, constructed on the Omo-Gibe River with a capacity of 1,870 MW, and the Grand Ethiopian Renaissance Dam, built on the Abay River with a capacity of 6,000 MW [18, 19].

Hydropower development has been prioritized as a key driver of economic growth in Ethiopia. However, to ensure the optimal efficiency of both existing and planned reservoirs, it is essential to assess the potential impacts of hydropower expansion. Ongoing changes in temperature, precipitation, and streamflow patterns increasingly affect hydropower schemes, influencing dam and reservoir design horizons as well as the operational life cycles of these facilities [20, 21]. Additionally, reservoir operating rules are widely applied to guide the effective management of hydropower systems [22]. Accordingly, several relevant studies have been conducted and are referenced in this review.

Tewodros Mekonnen (2022) analyzed hydropower development in Ethiopia and concluded that the country is already experiencing the adverse effects of climate change-induced droughts, which are negatively impacting its hydroelectric resources. To mitigate these effects, a 30% increase in total installed capacity would be required to compensate for an anticipated 50% reduction in hydro plant output due to drought. According to projections, by 2065, Ethiopia's electricity supply will comprise 9% from hydropower, 13% from nuclear energy, 3.4% from heavy fuel oil, 7% from geothermal, 6% from wind, and 5% from biomass. Despite the growing diversification of the energy mix, hydropower is expected to remain the dominant source of electricity generation until 2057, accounting for 25.2% of total output [23].

A prospective analysis of the power–water nexus indicates that the rapid construction of large-scale hydroelectric dams imposes environmental costs on downstream communities by altering natural water flow patterns. Simulation scenarios from the analysis reveal that, among Ethiopia's hydropower development pathways, two distinct modeling approaches are required to achieve projected outputs of 71 and 87 TWh per year by 2050 under a climate change mitigation scenario. These findings underscore the need to significantly increase installed capacity in Ethiopia to make a meaningful contribution to global efforts aimed at achieving the 2°C target of the Paris Agreement [24]. For comparison, Ethiopia's hydropower production stood at approximately 21 TWh per year in 2022 [4].

Kinfe Mirani (2022) evaluated the hydropower potential at the Kesem Reservoir, which spans an area of 2,974 km^2. The study applied Representative Concentration Pathways (RCPs), specifically RCP4.5 and RCP8.5, to assess projected climate impacts over short- and long-term periods. Under RCP4.5, the maximum estimated energy production is 376.2 MWh in the short term and 370.5 MWh in the long term. Under RCP8.5, the corresponding values are 368.6 MWh and 363.5 MWh, respectively. It is important to note that the original baseline for hydropower generation was projected at 380 MWh [25]. Additional research supports these findings, showing that climate variability across 200 locations in Ethiopia's Nile sub-basin could result in precipitation changes ranging from - 14% to + 27% by 2050. These findings underscore the significant vulnerability of large-scale hydropower infrastructure to unpredictable climatic events, including both tangible and intangible construction-related costs [26].

Ethiopia's transmission network is undergoing significant expansion and modernization to support the country's ambitious electrification goals. The government now aims to achieve universal electricity access by 2030, revising its earlier target of 2025, with plans to connect 96% of the population to the national grid by that year. Transmission infrastructure is being reinforced through the construction of new substations, the upgrading of transmission lines, and the modernization of grid systems to accommodate increased loads and integrate variable renewable energy sources [27, 28].

Ethiopia possesses substantial hydroelectric potential, with a significant surplus available for export. However, the majority of the population resides in remote areas with limited access to electricity. Currently, the country generates approximately 4 GW of electricity from 11 large and 7 small hydroelectric plants. To achieve universal electricity access, national energy policy should prioritize small-scale hydropower, which may offer a more practical and decentralized solution to meet rural energy needs while promoting economic development in these communities [29].

However, Ethiopia's expansion of large-scale hydroelectric projects has raised concerns among neighboring countries, particularly those dependent on the Nile River. For instance, Egypt has strongly opposed these developments, citing potential disruptions to its historical water rights.

Tanzania

Tanzania, located in East Africa, is known for its cultural diversity, national parks, and rich historical heritage. One of the country's key strengths lies in its abundance of renewable energy resources. Consequently, Tanzania has successfully harnessed various sources, including biomass, hydropower, geothermal, solar, and wind energy. According to the 2021 Energy Resource Guide, the country's total installed electricity generation capacity was 1,602 MW. Of this total, 244 MW were added over the previous four years, with capacity distributed as follows: hydropower – 568 MW, thermal – 951.6 MW, and other renewable sources – 82.4 MW [30].

Tanzania's electricity generation is primarily sourced from natural gas (48%), hydropower (31%), oil (18%), solar energy (1%), and biofuels (1%). This energy mix has contributed to improved electricity access, reaching 36.4% of the urban population and 11% of the rural population [31]. However, the country's continued reliance on hydropower, combined with frequent droughts, often results in power outages. In addition, Tanzania's average per capita electricity consumption remains low at 108 kWh per year, compared to the global average of 2,500 kWh per year [30].

According to Baraka Kichonge (2018), Tanzania is among the fastest-growing economies in Africa. To meet its rapidly increasing energy demands, the country requires affordable, clean, and, most importantly, sustainable electricity. Although thermal generation continues to dominate global electricity production, Tanzania has substantial hydropower potential, estimated at 38,000 MW. Nevertheless, as of 2021, only a small portion of this potential had been developed, with an installed capacity of just 562 MW [4], [32].

Research indicates that in Tanzania, the construction of hydroelectric plants and reservoirs has effects that extend well beyond direct environmental impacts. These developments often require the resettlement of communities and the displacement of wildlife, underscoring the competition for water resources between local populations and hydropower operators. Furthermore, the expansion of infrastructure associated with such projects is frequently linked to increased deforestation [33].

On the other hand, Tanzania's untapped hydroelectric potential, supported by feasibility studies estimating approximately 4,765 MW for development in the short to medium term, should be evaluated within the broader context of an integrated energy grid incorporating various renewable sources. However, frequent climatic challenges can negatively impact large- and medium-scale hydropower projects. The research highlights the important role that small-scale hydroelectric plants can play in both electricity generation and environmental conservation [32].

Reuben Kadigi (2008), in a study of the Great Ruaha River in Tanzania, assessed the value of water in irrigated paddy fields and hydropower generation using a residual imputation model. The estimated productivity of water (PW) in irrigated paddy ranged from 0.126 to 0.265 kg/m^3 while in hydropower generation it ranged from 0.45 to 1.68 kWh/m^3. These results underscore the importance of evaluating water's value across alternative uses to guide effective resource management and allocation [34]. Matthew England (2019) further emphasizes the need to integrate water use decisions across sectors, particularly in agriculture-based economies. In such contexts, resource reallocation can result in substantial transfers from agriculture to sectors with higher economic returns, such as hydropower and industrial production, potentially maximizing pro-poor outcomes [34, 35].

Tanzania is actively expanding its energy grid and transmission network to meet growing demand, with a focus on integrating renewable energy sources and enhancing regional interconnections. However, current conditions vary considerably across the country due to regional economic disparities, which affect the pace and effectiveness of infrastructure development [36, 37].

Given its geographical position and substantial hydroelectric potential, Tanzania is well-positioned to leverage clean, domestic energy resources. These assets can play a significant role in advancing national development goals and mitigating the effects of climate change. Nonetheless, to ensure sustainable progress, it is essential that hydropower initiatives provide meaningful and equitable benefits to both local communities and the environment, thereby supporting long-term growth in sustainable electricity generation.

Zambia

In 2020, Zambia's total installed energy capacity reached 2,800 MW, with hydropower accounting for 2,380 MW, or 85% of the total. In 2019, hydropower generation totaled 13,678 GWh [38]. Hydropower is a key component of Zambia's energy system due to its clean, renewable nature and its effectiveness in regulating power frequency. Zambia, a landlocked country in Southern Africa, borders eight neighboring nations. Its location near the equator gives it a tropical climate, with annual rainfall ranging from approximately 600 mm in the south to 1,400 mm in the north. December and January are typically the wettest months. In recent years, the country has increasingly faced extreme weather events, including recurrent droughts and floods [11], [39].

Nevertheless, research by Frank Mudenda (2022) indicates that fluctuating climate cycles are having increasingly adverse effects on Zambia's rivers, streams, and infrastructure. In recent years, the country has faced a growing electricity deficit caused by persistent power shortages. As of 2019, more than 1.9 million households (57.6%) remained without access to electricity, and over 96% of the rural population was still unelectrified. These figures underscore the critical need to address energy access and pursue sustainable electrification strategies [40].

Damaseck Chirwa (2023) observes that as Zambia's population grows, so does the demand for energy services, particularly electricity. This demand is expected to increase significantly, with the population projected to reach 26.9 million by 2035. Statistically, energy consumption is rising at an estimated rate of 6% per year, driven by demographic and socioeconomic factors [41]. As of 2020, the country's energy generation mix included coal (10.96%), heavy fuel oil (3.65%), diesel (2.78%), and solar (2.96%) [41, 42].

Scott Winton (2021) analyzed the Zambezi River Basin in Southern Africa, a region undergoing rapid development and population growth. Agricultural intensification, urban expansion, and the planned development of additional hydropower dams are likely to degrade the quality of surface water. However, there have been limited comprehensive assessments identifying where, how, and why specific water quality parameters are being affected, especially using in situ data across large regions. To address this gap, Winton conducted four field campaigns in 2018 and 2019, sampling a wide range of biogeochemical water quality parameters at 14 sites across central and southern Zambia. The findings indicate that while the major rivers, Zambezi and Kafue, exhibit low solute concentrations and are generally clean, they are impacted by thermal alterations, hypoxia, and the depletion of suspended sediments downstream of dams. Zambia currently hosts several large hydropower projects on these rivers, with a combined potential capacity exceeding 2,800 GWp, and additional feasibility studies are underway. Although such infrastructure is essential to strengthening the national energy grid and promoting clean energy development, it is recommended that these projects adhere to sustainable development criteria to minimize environmental impacts [43, 44].

Zambia's electricity grid depends largely on hydropower. The country is actively expanding and modernizing its transmission infrastructure to minimize energy losses and enhance reliability, often in coordination with regional power pools. Reports indicate that Zambia has achieved a low transmission loss rate of just 4%, and its national grid now covers nearly the entire country [45, 46].

At the same time, the country faces growing risks of water quality degradation due to increasing agricultural intensification, urbanization, and continued hydropower development. To address these challenges, it is essential for the Zambian government to invest in sustainable infrastructure and environmental management practices. These include wastewater treatment systems, ecologically sound dam operations, and the protection of watershed areas to preserve water quality and ecosystem health.

Zimbabwe

Zimbabwe has made notable progress in developing its energy infrastructure; however, this progress has not kept pace with the country's economic growth. As a result, Zimbabwe continues to face an energy shortfall, with an estimated national demand of 2,200 MW that it has yet to meet [47, 48].

Given the favorable climate conditions and the abundance of water bodies, Zimbabwe possesses substantial potential for hydropower development. However, this potential remains largely untapped due to the high capital investment required and a transmission grid that does not adequately reach viable generation sites. Furthermore, aging infrastructure and frequent power outages further limit access to renewable energy. Ongoing efforts to rehabilitate and expand the transmission network aim to improve both energy access and reliability [49].

According to the Zimbabwe Power Company, most of the country's electricity is generated by coal-fired thermal plants and hydroelectric projects, which are owned either directly or indirectly by Zimbabwe Electricity Supply Authority (ZESA) Holdings. However, due to constrained domestic supply, caused by economic challenges and insufficient investment in key infrastructure, Zimbabwe continues to import electricity from South Africa, Namibia, and Mozambique [50].

In Zimbabwe, forests are essential for both absorbing greenhouse gases and supplying energy, particularly in rural areas where 94% of the population depends on wood fuel. As a result, reconciling climate change mitigation with the goals of energy security and expanded electricity access presents a complex and pressing challenge that requires careful analysis [47].

Anesu Maronga (2021) examined the effects of drought on Zimbabwe's electricity supply, focusing on the Hwange hydropower station. The drought reduced the reliability of electricity generation, resulting in load-shedding that negatively impacted mining operations reliant on a constant power supply. The study evaluated the technical and economic viability of deploying concentrated solar power with thermal storage, as well as photovoltaic systems with battery storage, at a mining site in Zimbabwe. The findings concluded that integrating battery storage with a photovoltaic system significantly increases the proportion of the electrical load met by the renewable energy system [51].

Ekandjo (2018), in a study conducted along the Zambezi River within the renowned Mana Pools National Park, observed significant ecological and morphological changes over the past decade due to the construction of upstream hydroelectric dams. The study found that reservoir operations reduced average peak flows by 17% and increased average low flows by 5% in the Mana Pools area [52]. This analysis focused on Zambia and Zimbabwe, two Southern African countries that share the Zambezi River. In 2021, Zambia reported 2,703 MW of installed hydropower capacity, while Zimbabwe had 1,081 MW [4]. The study also confirmed that dams in and around both countries present various vulnerabilities. To mitigate ecological disruption, the study recommends aligning hydroelectric operations with wildlife management practices, particularly during flood control releases. Sudden gate openings were found to significantly disturb ecosystems, threatening both terrestrial and aquatic species [52].

Randall Spalding-Fecher (2016), in a study on the Zambezi River, highlights that water flow patterns are likely to shift in the future due to the significant impacts of climate change. These changes have serious implications for hydropower potential, as the financial viability and repayment of loans for related projects will depend on the stability of hydropower generation and revenue from energy sales. For example, the Kariba Hydropower Plant, shared by Zambia and Zimbabwe, is projected to be highly vulnerable to dry climate scenarios, with average electricity generation potentially decreasing by 12% between 2050 and 2070 [53].

In Zimbabwe, efforts to expand hydropower through renewable systems face additional challenges. The COVID-19 pandemic has led to higher infrastructure costs and increased land requirements, nearly doubling initial estimates. As a result, while the country gradually invests in new renewable energy projects, it is essential to keep all existing hydroelectric plants fully operational.

3.1. Discussion

Across the globe, continents are transitioning toward low-carbon economies centered on renewable energy technologies. In Africa, rapid population growth and economic development are driving a substantial increase in electricity demand. Consequently, the coordinated development of renewable energy offers a strategic opportunity for the continent to meet its growing energy needs while preserving environmental sustainability [54].

Although the African continent contributes the least to global warming, it is already facing some of the most severe impacts of climate change. Africa is home to nearly one-fifth of the world's population, yet it is responsible for less than 3% of global energy-related carbon dioxide emissions, with the lowest per capita emissions of any continent [9].

Although the adverse effects of climate change are being felt across Africa, countries such as Ethiopia, Tanzania, Zambia, and Zimbabwe are experiencing these impacts disproportionately. These include water stress, reduced food production, more frequent extreme weather events, and fluctuating economic growth. Despite these challenges, it is evident that these nations must continue pursuing economic and social development while contributing to the global clean energy transition [55, 56]. Hydropower is widely regarded as a clean, renewable energy source that offers benefits such as water supply, flood control, economic growth, and recreation [57]. However, the relationship between hydropower and external environmental factors is characterized by constant and often unpredictable fluctuations [58].

Comparing the findings from Ethiopia, Tanzania, Zambia, and Zimbabwe with broader global projections, Hamududu (2012) analyzed data from 12 global circulation models and found that significant changes in runoff are expected globally. For instance, large increases are projected in Quebec, Canada, while notable decreases are anticipated in Turkey and Venezuela, regions that previously exhibited high runoff levels. These changes are likely to have a direct impact on hydropower generation due to shifting hydrological patterns. The models further suggest that by 2050, hydropower production could decline by approximately 0.48% in Southern Africa, 0.83% in Northern Africa, 1.43% in Western Asia, and about 2% in Europe [59].

In comparison with other countries, a study in India projects a significant temperature increase of 6,25 ± 1,62 °C, which is expected to reduce river flows and negatively affect hydropower production during May and June, particularly at the Nathpa Jhakri and Bhakra Nangal plants, both located in snow-dominated regions [60]. In North America, reductions in hydropower output are also anticipated, driven primarily by hydrological changes rather than economic factors such as recessions. This is because hydropower systems generally operate continuously when sufficient water is available; however, increasing climate variability is affecting streamflow reliability [61].

Nevertheless, Africa holds the largest untapped hydropower potential in the world. According to a report published in June 2022 by the International Hydropower Association, this potential is estimated at 474 gigawatts (GW), compared to 73 GW in Europe, 275 GW in South America, 387 GW in North and Central America, 359 GW in East Asia and the Pacific, and 355 GW in South and Central Asia. While Africa's hydropower potential exceeds the continent's current and medium-term energy demand, the cost of electricity generated from hydropower remains among the lowest of all renewable sources globally [62, 63]. Therefore, it is recommended that Ethiopia, Tanzania, Zambia, and Zimbabwe coordinate the development of feasible hydropower resources and consider the findings of various studies, particularly those addressing the current and projected impacts of climate change.

According to the International Renewable Energy Agency, an additional 850 GW of hydropower capacity must be developed by 2050 to meet the climate goals outlined in the Paris Agreement. In 2020, 53 African countries submitted nationally determined contributions (NDCs) to the United Nations Framework Convention on Climate Change, collectively committing to mitigate 550 million tonnes of CO_2 by 2030. This target represents approximately 40% of the continent's current carbon dioxide emissions [9].

Moreover, the Africa Energy Outlook projects that by 2030, renewable sources, including solar, wind, hydropower, and geothermal, will account for over 80% of new power generation capacity. However, a key issue that warrants attention is the development of non-conventional renewables, particularly solar and geothermal energy. Although Africa holds 60% of the world's highest-quality solar resources, it accounts for just 1% of installed solar photovoltaic capacity. Solar energy, already the most cost-effective power source in many regions of Africa, must outcompete all other energy sources across the continent by 2030 to ensure sustainable development [64, 65].

Derrick Danso (2021) notes that hydroelectric power plants with large reservoirs are often used to support the integration of significant amounts of renewable energy, despite the inherent variability and intermittency of these sources. An evaluation of large hydropower reservoirs in West Africa indicates that when electricity demand increases by less than 25%, the combined contribution of solar and wind energy to total generation remains below 20%. This suggests that rising electricity demand can lead to instability in energy networks, particularly when they rely on a complex mix of renewables, fossil fuels, and other sources [66].

The energy transmission network in each country plays a fundamental role in enabling the efficient delivery of electricity from generation sources, including renewables, to demand centers, thereby ensuring a reliable power supply. For Ethiopia, Tanzania, Zambia, and Zimbabwe, a robust and modern transmission infrastructure is especially important to support economic growth, facilitate the integration of renewable energy, and achieve national development and electrification targets. Inadequate transmission systems can lead to bottlenecks, increased energy losses, and limited access expansion, ultimately hindering progress toward each country's development goals [67, 68].

This review highlights hydropower as a promising energy source with significant development potential across Africa. The analysis, which focuses on Ethiopia, Tanzania, Zambia, and Zimbabwe, underscores the need for broader integration of sustainability criteria. However, by covering only four of Africa's 56 nations, the review offers a limited perspective on the continent's overall hydropower landscape.

4. Conclusions

In Ethiopia, Tanzania, Zambia, and Zimbabwe, where hydropower has received substantial investment, climate change poses a significant challenge due to increasingly variable hydrological patterns. Power utilities in these countries must not only project future energy outputs but also implement comprehensive mitigation and adaptation strategies to protect infrastructure. Across all climate scenarios, projections indicate a declining trend in hydropower capacity driven by climatic variability.

In Ethiopia, concerns over transboundary water rights have sparked regional tensions, particularly with countries such as Egypt that depend heavily on Nile waters. Tanzania, by contrast, regards hydropower as a key driver of clean energy development, given its potential to support economic growth and reduce vulnerability to climate change.

In Zambia, the intensification of hydropower development raises concerns about declining water quality, highlighting the need for sustainable infrastructure investments such as wastewater treatment facilities, environmentally conscious dam operations, and basin protection zones. Zimbabwe, meanwhile, faces mounting challenges related to high installation costs, land requirements, and post-pandemic constraints, all of which hinder the expansion of its hydropower sector.

Given the critical role of climate change as an external variable, it is essential to evaluate hydropower generation and reservoir operations using key parameters such as temperature, precipitation, humidity, river flow, and basin characteristics. These indicators provide foundational data for designing resilient and efficient hydropower systems. In addition, African countries are encouraged to explore solar energy, as the continent holds 60% of the world's most valuable solar resources, offering a complementary path toward sustainable energy development.

While hydropower offers a reliable pathway to energy access and socioeconomic advancement for countries like Ethiopia, Tanzania, Zambia, and Zimbabwe, its development must ensure tangible benefits for local communities and ecosystems to be truly sustainable. Future research should explore the integration of other renewable sources across the continent, supported by green financial mechanisms that can accelerate Africa's transition to a diversified and sustainable clean energy future.

Contributor Roles

- **Sebastián Naranjo-Silva:** Conceptualization, data curation, formal analysis, investigation, writing – original draft, writing – review & editing.

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