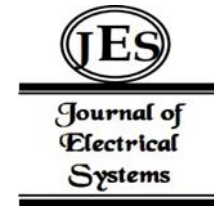


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## An Outlook of Recent Sub-Saharan Africa's Hydroelectric Power Development and Inherent Challenges: A Geospatial Review.



**Abstract:** - Sub-Saharan Africa (SSA) is home to more than 1.21 billion people and is the world's youngest and fastest-growing population. Although it possesses vast potential for hydroelectric power (HPP) development, it still faces an extreme energy deficit. As global and regional collaborative efforts are being exerted to electrify the region and decarbonize its energy sector, this review aims to provide a visual representation of the extent of development observed in recent years and the associated challenges potentially impacting its sustainability. Using the interpolation algorithm in ArcMap, a comparative analysis between three spatially referenced datasets, namely, potential, harnessed, and existing capacities, was performed. These data were obtained from the Renewable Power Plant Database for Africa (RePP Africa), the International Hydropower Association (IHA), and the Global Energy Monitor (GEM), respectively. Out of several highlighted challenges, climate risk is emphasized by assessing a 2-decade (2001–2020) period of precipitation and temperature from the Climate Research Unit (CRU). As of 2022, 19.6% (35.248 GW) was harnessed out of the estimated potential HPP capacity (179.782 GW). This represents a developmental rate of ~9.7% from 2019 to 2022. Compared with the harnessed capacity, the existing capacity in 2023 exceeded 0.68 GW, a difference of 1.061 GW, which is attributable to HPPs with capacities less than 75 MW. Climate risk assessment revealed that temperature and precipitation increased by 2.42% (0.6 °C) and 5.97% (49.43 mm, respectively). Despite the mixed spatial distribution of these developments and potential challenges, the grid transboundary transmission and distribution (T&D) of SSA have proven promising. However, environmental, socioeconomic, political, and policy-based repercussions associated with these inherent challenges already require robust solution-based decision-making.

**Keywords:** Climate Change, Electricity Grid, African Power Pools, Renewable Energy, Sustainable Development.

### I. INTRODUCTION

Industrialization caused a massive change in the world economy, resulting in a substantial increase in energy consumption, the majority of which came from nonrenewable sources [1]. There was a recognized need for lowering greenhouse gas (GHG) emissions from nonrenewable sources, which led to international collaboration in formulating the Paris Climate Change Agreement (PCCA) in 2015 [2–4]. With their 169 targets, the 17 Sustainable Development Goals (SDGs) represent the aspirations of the agreement, paving the way for future development from 2015 to 2030 and beyond. To achieve the climate-centric aspects of the agreement, it is crucial to move from the old forms of energy production and consumption as identified in the United Nations Framework Convention on Climate Change (UNFCCC). However, the importance of energy as a driver of economic growth and development cannot be satisfied in time. Major consumers, who are compelled by the necessity of decarbonizing their economy and bringing clean and affordable energies into practice, have started with initiatives to cut their consumption of nonrenewable energies [5–7]. Among many other alternatives, hydropower has become the most harnessed renewable energy resource in many developed and developing nations due to its ability to provide environmentally friendly operation, reduce fossil fuel usage, and help mitigate global warming. However, many member states of the UNFCCC remain less advantaged, with Africa, especially SSA, being the most important region of interest. As a result, studies on the development of renewable energy in SSA have become increasingly important. A continental assessment suggested that Africa's electricity demand will grow exponentially in the next few decades [8]. Additionally, it is projected to increase from a capacity of 115 gigawatts (GW) to approximately 700 GW by 2040. In its 2020 report, the International Energy Agency (IEA) stated that hydropower makes up 17% of the continent's power and is expected to increase to 23% by 2040. Sub-Saharan Africa has the highest population growth rate on the continent, with approximately 1.21 billion people, a number that is expected to double by 2050 [9,10]. To satisfy future energy demand, many African nations, motivated by population growth and the desire to improve living standards, now opt for an expansion in their power generation capacities. This expansion amounts to approximately 5 to 6%, with more than 300 new projects under consideration, particularly in SSA [11]. Unlocking the full potential

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of hydropower requires more than just a coordinated approach among member states. The reliability, safety, and efficiency of existing and proposed HPP necessitate innovation and extensive research to streamline governance, investment, policy, and successful implementation. Additionally, the availability of sector-specific information is important for design selection and resource allocation; it also encompasses climate risk-informed decisions that enhance project sustainability. To date, numerous reviews and studies have sought to explore the vast potential of SSA hydropower. However, it is well known that the development of SSA hydropower development comes with several challenges, ranging from socioeconomic to technical and environmental concerns. Several probes have extensively discussed the existing resource potential and investment in African power pools (APPs) [12–14]. Conversely, other researchers have expressed concerns about the current and potential difficulties associated with SSA projects [11,15–19]. Their studies on HPP development primarily emphasize APP's expansion, while there are forces in existing and emerging challenges for HPPs, along with control mechanisms. In contrast, visual results are easily and quickly interpreted compared to those in the literature, but spatial patterns of development and challenges are often missing from the previous literature. Geospatial surveys, such as those conducted by Kebede [20], while assessing the potential of Ethiopian HPP in the Gumara River basin and others in SSA regions, are often made at the country level, which does not reflect the true potential of SSA.

As the SSA is a highly dynamic environment, choices tailored to the past but also reflecting known climatic conditions and future scenarios can help decision-makers and developers make plans for inevitable change. Climate risk-informed decisions are known to attract investment and ensure sustainability. Therefore, this review synchronizes the literature and data to achieve two main objectives: 1. Present geospatial distribution of the current HPP development and the estimated rate at which it has developed in recent year 2. Highlight and discuss existing and potential challenges, and implications in developing SSA's hydropower sector. Among these challenges, we emphasize climate risk by assessing two decades of precipitation and temperature data. We used existing resources to derive answers, which are tangible and readily available.

## II. LITERATURE REVIEW.

The review of previous literature is organized into two parts: 1. Overview of the development and prospects of HPP in the SSA region. 2. Overview of the challenges in the development of HPP in the region.

*HPP development and prospects.* The GEM report of June 2024 estimates that, there are 1,133,406 megawatts (MW) of operating hydropower plants in Africa, Asia, America, Europe, and Oceania. The potential projects add up to 1,088,735 MW, with 23.03% under construction, 48.57% in the preconstruction stage, and 28.39% announced. Conversely, there are 49,470 MW shelved, 9,945 MW mothballed, 773 MW restarted, and 64,115 MW cancelled projects across these continents [21]. These statistics specifically cover hydropower plants with a capacity of 75 MW. The share of operating projects in Africa is 3.3%, with 0.54% in North Africa and 2.76% in Sub-Saharan Africa. Africa also has 4.73% of prospective projects. It is important to note that this information may not fully represent the potential of hydropower in Africa, as it does not cover numerous small hydropower plants (SHPs) on a microscale. [22–25]. With the bulk of its energy yet originating from nonrenewable sources, which are capital intensive and polluting, the program for infrastructure development in Africa (PIDA) endorses modernization and an interconnected large-scale HPP as a source for flexible and clean energy, which could reap a yearly reduction in the cost of energy production by US \$30 billion [26]. In recent years, the African Development Bank (AFDB) has made significant investments in the expansion of capacity in SSA. China has also been instrumental in the development scheme and has completed approximately 150 new capacities for continental transmission and distribution (T&D) [12,13]. Fig. 1 illustrates the dimensions and capacities of both planned and existing high-voltage (HV) T&D lines delineated by lines with lengths greater than 30 kilometers (km) and capacities between 90 and 765 kilovolts (KV's).

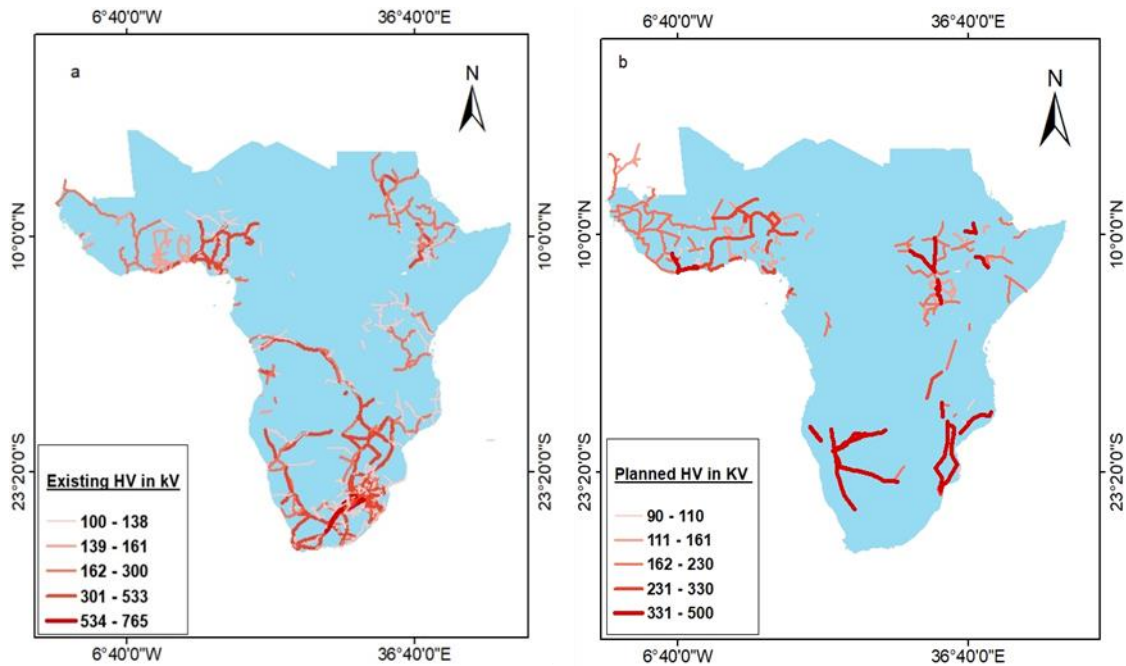


Fig. 1 a. Existing T & D. b. Planned T & D. Data source. [42]

The Africa Hydropower Modernization Program (AHMP) [27], which utilizes alternative strategies such as life extension, significant upgrades or upgrades, total redevelopment, and digitalization to upscale hydropower generation (HPG), suggests that reinvesting and modernizing existing assets are part of its objective. The implementation of these strategies is inherent in the APP scheme, which is distributed across five regional power pools, including the North African Power Pool (NAPP), Southern African Power Pool (SAPP), Eastern Africa Power Pool (EAPP), West African Power Pool (WAPP), and Central African Power Pool (SAPP) [28]. These frameworks have developed due to the unequal distribution of renewable energy potential and the need to centralize the continent's energy production. Since the establishment of the subdivision, energy development and production through the provision of new HV transmission systems have proven beneficial.

#### *Challenges in the development of the SSA HPP.*

Despite the formation and operation of these bodies, the SSA energy sector is still predominantly characterized by oil, gas, and coal [29–31]. These studies reveal that in many parts of SSA, the oil and gas business is seen by individuals as the fastest wealth-generating activity due to its extreme dependency and high profit margin. The impact of dependency also extends to the governmental level, as the generated revenues significantly contribute to the economies of heavily import-driven SSA states. Even though oil and gas seem to constitute a perfect market, studies further suggest that they inadvertently affect the government due to their high volatility and environmental implications. In many cases, they have narrowed interest in unilateral investment in large-scale renewable energies, which often appear slower and require enormous initial capital investments [12,13]. Given that the enormous hydropower potential in SSA is still underexploited and under researched, the United Nations Industrial Development Organization (UNIDO) panels view investment in small hydropower plants (SHPs) as a step that essentially promotes climate-centric development that encompasses the available grid energy for rural communities, industrial development, and the initiation of climate-smart agriculture [14]; however, to date, consistency and efficiency in the development of hydropower remain disproportionately distributed at the continental, regional, and country levels. It is further emphasized that while other sub-Saharan nations tend to benefit, countries such as Liberia, with its six major rivers, still have more than 75–85% of their citizens without access to the electricity grid. Nigeria is another state challenged by a lack of electricity, and harnessing the SHP is seen as an opportunity that not only provides clean and affordable energy but also becomes a multipurpose scheme that provides job opportunities [32]. Kabo-Bah et al [33] argued that the centralized energy framework is also unevenly distributed in terms of capacity and rate of development. Furthermore, while the majority of APPs are still at an embryonic stage, EAPP, NAPP, and SAPP remain the most advanced schemes, accounting for more than 75% of the

continent's power. In West Africa, more than 50% of the HPG potential remains untapped, while some existing HPPs demand serious re-engineering to optimize productivity. Reportedly, hydroclimatic variability and the exacerbation of extreme weather events are among the climate-induced challenges that have adversely impacted the HPG capacity of major basins [11,15,16]. Similar findings were also reported by Obahoundje and Diedhiou [34]. They found that dynamic environmental conditions, such as uncertainty in precipitation and a reduction in streamflow in major basins, are projected to increase with sedimentation and siltation. Furthermore, the IEA ascertained that the continent as a whole is most susceptible to climate change, and the expansion of hydropower capacity could increase a nation's climate-related hazards and pose dangers to electrical systems if decisions for hydropower development are not made in light of the potential impact of climate change [35]. For instance, Leslie [36] reported that the Kariba Dam, one of the largest dams in Africa spanning Zambia and Zimbabwe, was facing prolonged drought and the risk of closure. Similarly, Hulsman P. et al [37] conducted a study and reported the lowest rainfall deficit and reservoir level in the Zambezi Basin, where Kariba is located. A similar study was conducted by Salami [38], who examined and identified a decreasing trend in the discharge of the Kainji River, home to the Kainji Dam in Nigeria, and suggested that this trend stemmed from fluctuating meteorological patterns. Moreover, Madu [39] argued that both planned and unplanned outages are the result of procedural, maintenance, and operational issues. This implies that technical challenges are also an extension to environmental issues, thus necessitating an inclusive solution. While transboundary development is seen as a climate-reliant strategy, Elabbas and Hafner [17,18] observed that the rate of interconnected development is influenced by factors such as climate change, technical challenges, weak transboundary regulations, political instability, and a lack of funding. This situation is mostly observed in the CAPP. In central African states, poorly developed and inaccessible electrical systems pose a challenge. Although the CAPP has initiated some hydro-based development in the region, it faces hindrances due to the inaccessibility of vital data [40]. Furthermore, the CAPP and EAPP are currently working on resolving energy deficits and deciding between synchronous and asynchronous interconnection. It has been noted that using a variety of penetration systems might not be beneficial for integrating power systems effectively. However, asynchronous penetration is preferred because it reduces emissions and the cost of pooling.

#### *Summary of the literature review*

The results from the screened literature present three major findings. (1) Studies accounting for the potential for hydropower in SSA suggest that the region is characterized by a vast basin with tremendous potential for HPP, which is still underexplored, thus making SSA one of the most unelectrified parts of the world. (2) Studies reveal that transboundary investment in power pools and the coordination of power systems could offset regional energy deficits and decarbonize the energy sector. (3) Implementing proposed developments while considering current technical, socioeconomic, and environmental challenges is crucial for promoting sustainability and corporate responsibility.

### III. METHOD AND DATA

#### *Study area*

The assessment focused on HHP development in 48 states with a total land area of 23.27 million km<sup>2</sup>. This study provides results on power pools, with the exception of Mauritania, a country in the SSA region that belongs to the NAPP, as indicated in Fig. 2. The figure illustrates the share of the power pools among member states. Islands are labeled pending, as they do not belong to any power pool yet.

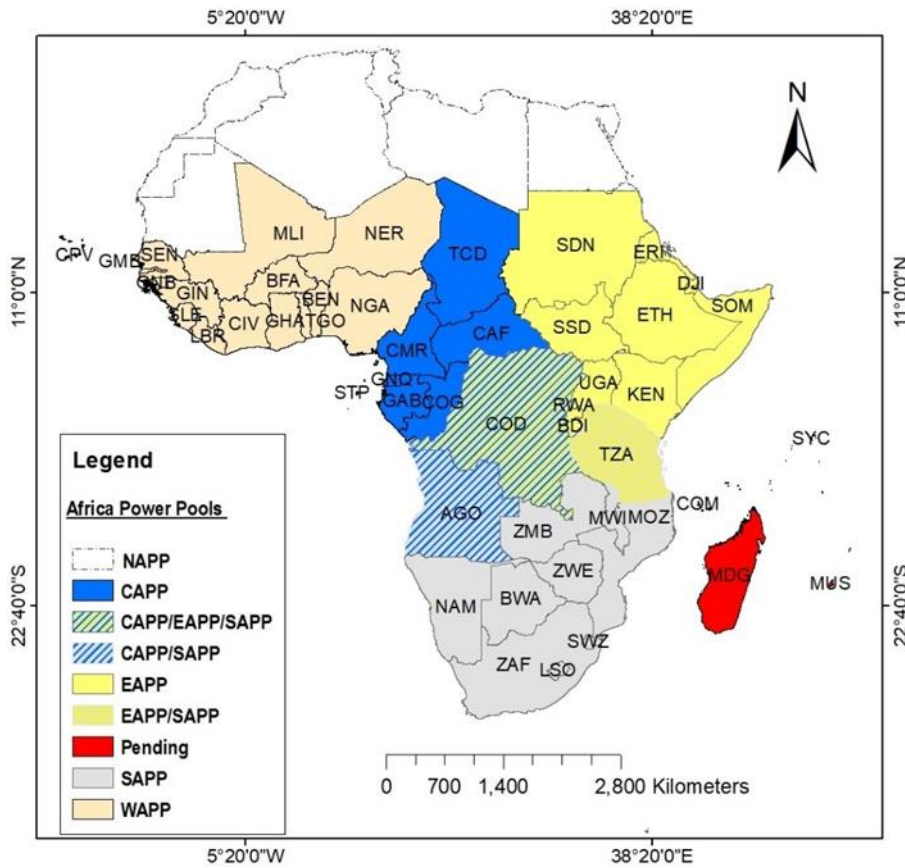


Fig. 2 Share of power pools and member states

*Data collection and preparation*

development, opportunities, and obstacles using key terminology in databases such as Springer, Web of Science, and Google Scholar, which is similar to the approach of Obahoundje and Diedhiou [34]. As shown in **Error! Reference source not found.**, HPP-related data were gathered from three major repositories, followed by geospatial analysis utilizing interpolation algorithms in ArcMap. The findings are further expressed through comparative analysis. The outlook of current development is described in 3 steps: (1) The harnessed capacity (available from <https://indd.adobe.com/view/>) was divided by the potential capacity (available from <https://springernature.figshare.com>) to calculate the percentage of harnessed capacity, which is also described as the percentage of HPP developed. It is given as

$$(1) \quad P_d = \frac{C_h}{C_p} \times 100$$

where  $P_d$  is the percentage of HPP developed,  $C_h$  is the harnessed capacity, and  $C_p$  is the potential capacity. We also used a global energy observatory (GEO) dataset (available from <https://datasets.wri.org/dataset>) as complementary data for the geospatial description of HPP development.

(2) The rate of development was derived as an estimate of the percent change observed from 2019 to 2022. Determination of the rate is based on the change in harnessed capacity observed over the given period. This is given as:

$$(2) \quad R_d = \frac{\Delta C}{C_{in}} \times 100$$

where  $R_d$  denotes the rate of development,  $\Delta C$  is the change in capacity over the given period, and  $C_{in}$  is the initial capacity.

(3) Existing and planned capacities (available from <https://globalenergymonitor.org/x>) were used to further describe the development and prospects and validate the results from the harnessed capacity. (4) Several challenges with the potential to impact sustainability are highlighted, while environmental challenges, particularly climate change, are examined to determine their impact on the HPPs of SSA. Two decades (2001–2020) of precipitation and temperature data from the CRU (available from <https://crudata.uea.ac.uk/cru/data>) were used to determine the

pattern of climatic conditions and its potential implications for HPP development and operation. These were partially generated using the interpolation algorithm and spatial analysis in ArcMap, such as that by Almazroui [41]. For each of the given parameters, we used the average values to calculate the percent change, following the method outlined in equation 2. A negative outcome indicates a decreasing trend, while a positive result shows an increasing trend. The findings are discussed for both holistic and decentralized power pool-specific scenarios, as shown in Fig. 2

Table 1 Data description and sources<sup>2</sup>

Data type	Description	Citation
Existing capacity & Planned capacity	A multisectoral dataset available upon request. Account for operating, prospective, and unused HPP $\geq$ 63 or 75 MW. Obtained from GEM	[21]
Existing HV & Planned HV	An open-source data that provide Africa's existing and planned grid electricity map. Provided by World Bank	[42]
Harnessed capacity	An open-source data portal, which comprises of 87 African HPPs. Provided by IHA. GEO's hydropower database provides geographical coordinates for over 35,000 HPPs globally.	[43,44]
Potential capacity	Integrated Africa's renewable energy data offering a spatial resolution less than 100 m	[45]
Precipitation & Temperature	Obtained from Climate Research Unit (CRU), offering a high resolution at 55.5 km X 55.5 km. It provides global monthly climate dataset	[46]

#### IV. RESULTS, VISUALIZATION, AND DISCUSSION

This section includes a visual representation of the parameter being assessed, its findings, and a brief summary of the findings, followed by a discussion

Potential and harnessed capacities.

Recently, the promotion of and investment in SSA through the AFDB, the International Renewable Energy Agency (IRENA), and China have gained momentum for SSA energy development. Noteworthy strategies include modernization and rehabilitation of existing HPP, expansion of transmission and distribution facilities, and transboundary power trading. However, the state of HGP is still far from meeting the needs of the population. **Error! Reference source not found.**a describes the known potential capacity <sup>3</sup> of the vast river body of SSA, with an inclusive capacity estimated at over 179.782 GW. The potential includes the estimated capacity of existing prospective projects.

<sup>2</sup> Both existing capacity and harnessed capacity are same as operating capacity, but use different nomenclatures to distinguish the GEM and IHA repositories. Potential capacity is the combination of operating and prospective HPPs.

<sup>3</sup> Known potential capacity is the combination of both the operating and proposed HPPs

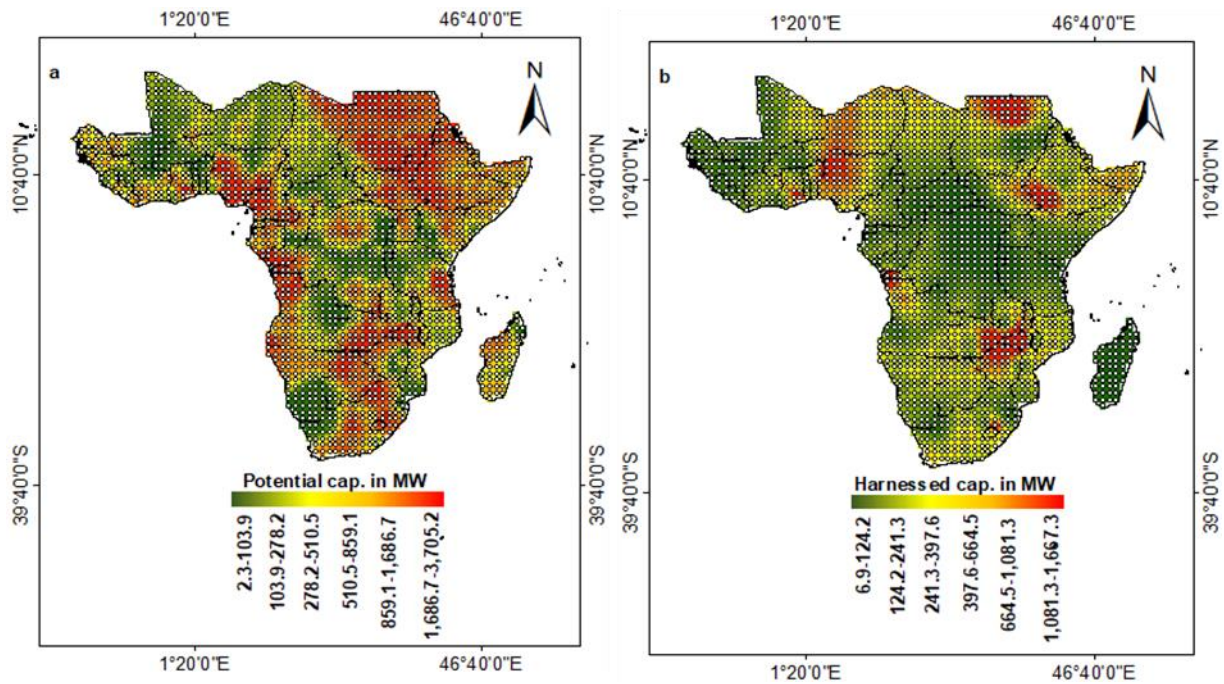


Fig. 3 a. Capacity of known potential. Data source (Peters et al. 2023). b. Harnessed capacity. Data source [43,44]

**Error! Reference source not found.** shows that the harnessed capacity, estimated at 35.248 GW. The percentage of HPP development is then estimated at 19.6%. Additionally, the HPP capacity increased from 32.134 GW to 35.248 GW between 2019 and 2022 [44,47], indicating an increase of 9.7%, which represents the development rate of hydropower. The results show that the upper northeastern parts of the WAPP, CAPP, and Kalahari region between South Africa and Namibia in the SAPP are hotspots of micro HPP and SHP, while the rest of the SSA may benefit from larger HPPs. The preference for SHPs in these regions is due to natural streamflow. Traditionally, the assessment of a river's energy potential is based on factors such as historical average discharge, meteorological conditions, and basin attributes, but many rivers are still unexplored and therefore not included in the potential capacity. However, it is believed that the majority of this unexplored potential is suitable for SHPs. According to Korkovelos et al. [48], the total potential for mini hydropower (0.1–1 MW) in the Democratic Republic of Congo, central region, and Angola is estimated at 3.421 GW, with the SHP estimated at 21.800 GW. They further observed that South Africa and the eastern region together make up one-third of the identified potential. This assessment, compared to **Error! Reference source not found.** and **Error! Reference source not found.**, demonstrates that while the continent possesses vast renewable energy potential, its spatial distribution remains uneven, necessitating the need for cross-border energy trade. The current and projected capacity assessments provide a clearer view of the uneven distribution. Information on existing and planned HPPs from GEM spans 81 operating HPPs larger than 75 MW and prospective, canceled, and shelved HPPs larger than 63 MW, as shown in **Error! Not a valid bookmark self-reference.** and Fig. 3.

Table 3 shows that there has been a significant increase in the existing HPP capacity in recent years, amounting to 3.260 GW between 2021 and 2023. An additional 12.464 GW is planned to be completed between 2024 and 2030, while approximately 48.953 GW are expected to be commissioned before Africa 2063. Furthermore,

Table 4 displays the number of HPPs contributing to the summarized capacity presented in **Error! Not a valid bookmark self-reference.**

Table 2. Summary of HPP capacity<sup>4</sup> data adopted from [21]

Status	Cap. in GW
Announced	19.677
Preconstruction	15.201
Construction	12.875
Operating	32.337
Shelved	5.284
Cancelled	7.928

Table 3. Latest development in HPP. from [21]

Country	Cap. MW	Commission
DR Congo	240	2021
Ethiopia	750	2022
Mali	140	2022
Nigeria	700	2022
Tanzania	80	2023
Uganda	600	2023
Zambia	750	2021

Table 4: Summary of HPP Counts by Power Pool. The data were obtained from [21]

Region	Operating	Construction	Preconstruction	Announced	Shelved	Cancelled
CAPP	6	2	8	1	3	4
SAPP	26	2	15	14	1	3
EAPP	31	3	6	16	9	8
WAPP	17	3	12	11	5	2
Pending	1	0	3	0	0	0
Total	81	10	43	42	18	17

In Fig. 3, member states are ranked according to HGP capacity. States ranked “0” indicate that there is no existing HPP that meets the GEM’s criteria. Somalia, for instance, has zero hydropower generation but possesses significant potential for solar power generation [49]. In the case of Rwanda, even though the majority of its river is characterized by lower streamflow, most of its hydropower has a capacity of 5 MW [50]. However, the Rwanda Energy Group (REG) estimates that hydropower contributes approximately 36.9% of the total energy [51], indicating that the SHP is the most harvested system. The CAPP remains the slowest and most underdeveloped power pool, despite the enormous potential of the SHP.

<sup>4</sup> (1) Announced projects are known but currently inactive. (2) Preconstruction refers to active projects seeking approvals, such as environmental impact assessments (EIA) and land rights. (3) Shelved projects are suspended or projects that have been dormant for two years. (4) Cancelled projects are those that have been announced as cancelled or have been dormant for four years. Projects at the announced, preconstruction, and construction statuses are grouped as prospective or planned capacity.

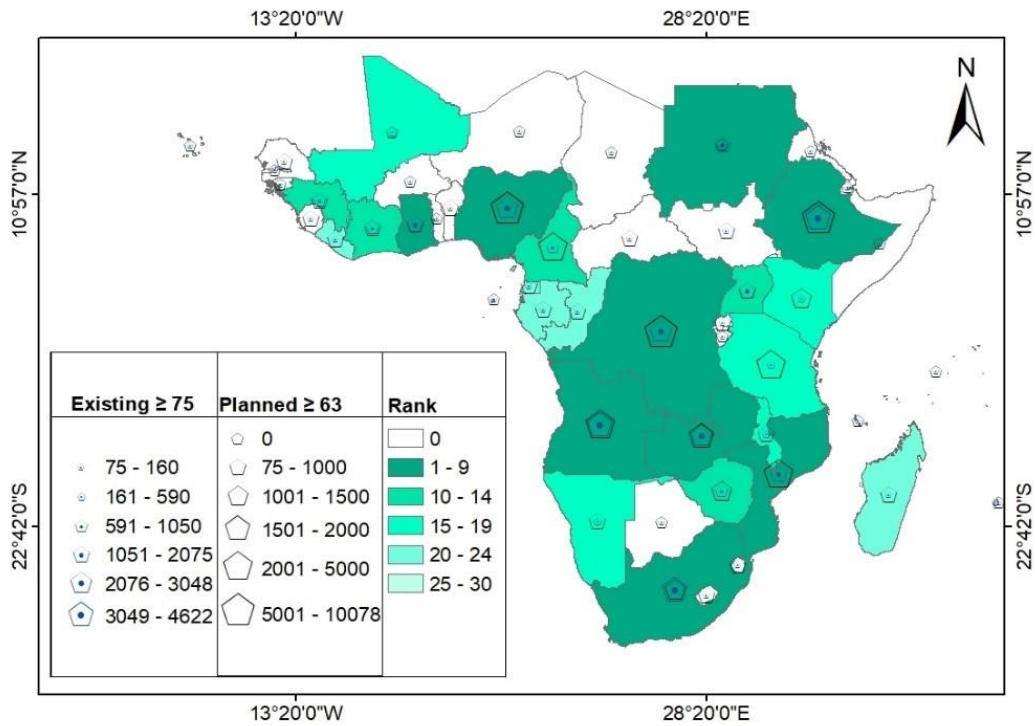


Fig. 3. National states of power development. Data source [21]

The report<sup>5</sup> of GEM shows that significant development occurred in 2023, primarily in Uganda (600 MW) and Tanzania (80 MW), setting the existing capacity at 34.187 GW. This implies an additional 0.68 GW of power capacity, which does not count toward the harnessed capacity described in **Error! Reference source not found.** As a result, the total harnessed capacity increased to 35.928 GW. When the harnessed capacity is set at 35.248 GW as of 2022, the existing capacity amounts to 34.187 GW as of June 2024, resulting in a difference of 1.061 GW. This difference may be explained by the number of HPPs with operating capacities less than 75 MW or a lack of data.

### Challenges in HPP Development

Previous research has highlighted the importance of understanding the current and upcoming challenges in developing renewable SSA. These challenges can be classified into five main categories: (1) environmental, (2) technical, (3) socioeconomic, (4) policy, and (5) political issues. Climate change is one of the significant environmental challenges that has drawn global attention for assessment. This is because it can lead to a seasonal reduction in streamflow, which is essential for HPG [52]. In this review, climate change risk assessment is considered a crucial topic.

### Assessment of climate change-induced challenges.

In the last three decades, many African HPPs have faced frequent power disruptions due to climate change and variability [34]. Although climate change has increased the risk of river desiccation and flooding, there is a growing reliance on hydropower and the need to expand capacity. However, the sustainability of HPP development has become doubtful, as current climate conditions are already affecting power generation, and future climate uncertainties tend to be extreme. Anderson [53] observed that basins that are more sensitive to meteorological phenomena are most likely to experience reduced streamflow with even slight changes in climate. In light of such conditions, Taner et al. [54] suggested that decision-making and criteria-setting for sustainability must be more representative of future

<sup>5</sup> This major development does not incorporate micro HPP and SHP.

scenarios, which can be achieved through global climate model (GCM)-based analysis. Such analyses are often based on historical trends to describe future plausible climate scenarios. This is why Almazroui [41] used the Coupled Model Intercomparison Project (CMIP6) to project Africa’s precipitation and temperature. The results from the CMIP6 multimodal ensemble showed that the continent’s temperature and precipitation have increased previously and will continue in a similar pattern.

In this review, we conducted such assessments using CRU data to determine the historical trend of these parameters over SSA. **Error! Reference source not found.** and **Error! Reference source not found.** show the historical spatial precipitation and temperature data collected from CRUs spanning two decades (2001–2020). The results revealed that the temperature increased by 2.42% (0.6 °C), while the precipitation increased by 5.97% (49.43 mm) over the two decades. These findings further convey the idea, results, and argument for climate-induced risk described in the literature review.

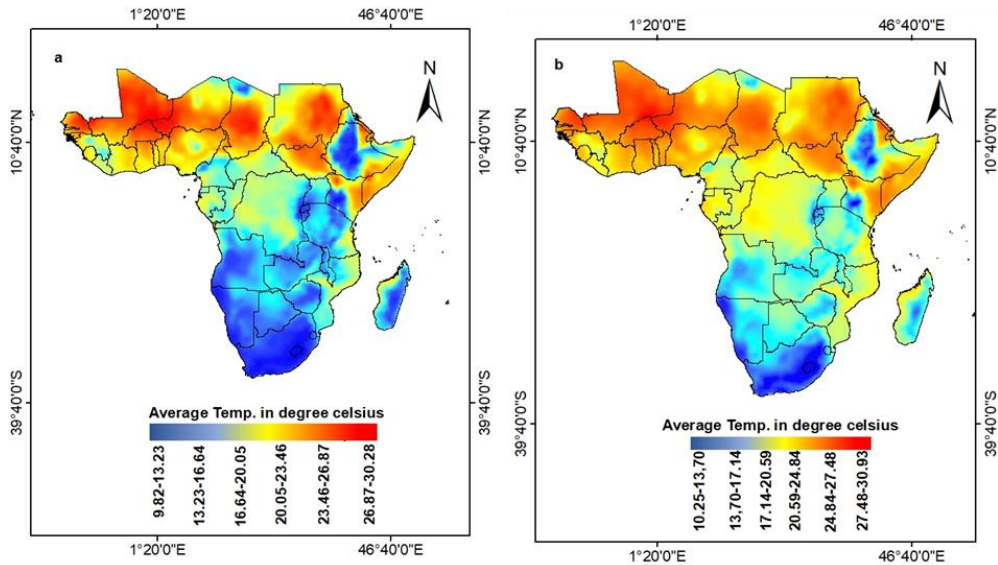


Fig. 5. Temperature profile of SSA. a. (2001-2010) b. (2011-2020). Data source [46]

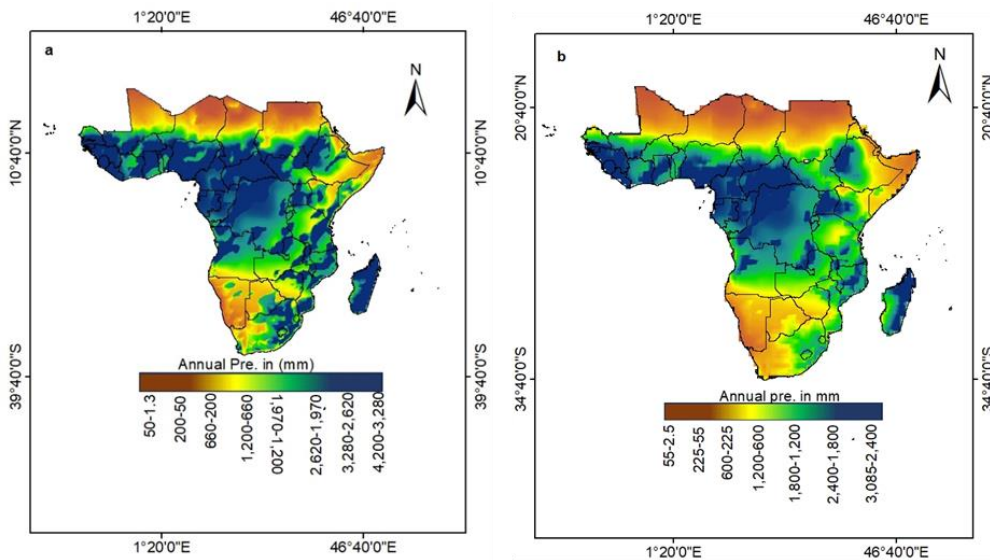


Fig. 6 Precipitation profile of SSA. a. (2001-2010) b. (2011-2020). Data source [46]

### V. DISCUSSION

#### . Roadmap for development and prospects.

The drivers of energy development go beyond the number of potential consumers and target the economy,

technology, skills, environmental adaptability, and resource availability. This is evidenced by the population of Sub-Saharan Africa. Despite being the world's youngest and fastest-growing population, it remains the most unelectrified region in the world. The energy deficit deepens as population growth necessitates settlement expansion, mechanization, and modernization activities, which offset the rate of development. While it was estimated that electricity is inaccessible to 900 million people, it was also suggested that approximately 530 million people will still lack access to electricity in 2040, with the majority from SSA. [55]. A 14-year (2014–2030) forecast by Wang [56] suggested that energy demand in central Africa alone will increase by approximately 5.37%. The growing demand amid the unreliability and inaccessibility of electricity impedes economic growth and development, with consequences ranging from the continental to individual levels. Given the enormous untapped potential of renewable energy, it is an opportunity that plays a pivotal role in electrifying SSA, contributing to goal 7 of the SDGs, and reaching the net-zero emission target. The need to comply with the UNFCCC-Kyoto protocol under the Clean Development Mechanism (CDM) has sprawled through the continent, creating interest in several investments in renewable energy development. Hydropower is now the most harnessed and developing renewable energy in SSA. Often, national economic status creates divergent interests, but hydropower development seems to lie at the heart of every SSA leader. Although the installed capacity doubtfully makes up to 12% of its estimated full potential, there has been slight regional progress. The 19.6% in harnessed capacity, in terms of percent of development, is comparable to the known or assessed potential (179.782 GW). As a result, it is limited and cannot be extrapolated to the full hydropower potential of SSA hydropower. Nevertheless, it is an indicator of growth. Although the distribution of growth rates is extremely uneven, the implementation of the objectives of regional economic communities (RECs) through power pools has taken a robust trajectory into energy development using interconnected systems. This could have a massive impact on the SSA energy sector, as it is a scheme expected to promote the full development of Africa's grid electricity through cross-border transmission. Currently, hydropower contributes approximately 20% of the region's total energy generation, with more than 100 GW planned to be produced by more than 300 projects [11]. This estimate differs from that of

Table 4. According to

Table 4, the total planned capacity for combined future projects is 95, which suggests that most proposed HPPs may have a capacity of less than 75 MW. This finding also provides further evidence that SSA may have tremendous potential for use in SHP. Overall, these results indicate a promising future for HPP development. The integration of power systems, as witnessed through the planned T&D lines, has improved SSA's shared grid. Countries such as Burundi, Sudan, and most West African states are envisioned to benefit from the interconnection. Currently, Ethiopia has the largest installed capacity of 4.864 GW, with more than 10.078 GW of prospective capacity. Despite its internal energy deficit, the nation exports energy to Djibouti, Kenya, and South Sudan at rates of 300 MW, 400 MW, and 100 MW, respectively. The capacity of the EAPP is expected to increase tremendously upon the completion of the Grand Ethiopian Renaissance Dam (GERD), with an estimated capacity of 5.150 GW [57], and others, such as the Inga Dam in the DRC situated on the Congo River, with an expected capacity of 4.8 GW and full-scale operation projected to 40 GW.

The SAPP and WAPP have combined prospective capacities of more than 20 gigawatts (GW), which is expected to significantly reduce the energy deficit by 2030. Within the SAPP, Mozambique, Zambia, and South Africa have planned capacities of 3.43 GW, 2781 GW, 1.5 GW, and 1.2 GW, respectively. Similarly, Nigeria is the most industrialized nation within the WAPP, with a prospective capacity estimated at 8.23 GW. Additionally, countries such as Guinea, Côte d'Ivoire, Sierra Leone, and Liberia are among the nations with planned hydropower projects. However, the timeframes for these proposed projects are mostly uncertain. Meanwhile, the future growth of the CAPP is highly uncertain, but Cameroon, as its most advanced nation, has some planned capacity set at 2.578 GW, followed by Gabon and the Republic of the Congo. In addition to transboundary connections, many SSA nations have now instituted rural energy development schemes, which tend to operate at the national level, promoting the installation of SHPs to serve communities. The growing demand, dependency, and hydropower development necessitate a

rigorous sustainability evaluation to understand the tradeoff between present and future plausible consequences and socioeconomic benefits.

### *The impacts of challenges.*

Although hydropower development has attracted the interest of African leaders and has become an essential catalyst for achieving Africa by 2063, there are undeniable inherent challenges, encompassing socioeconomic, political, technical, and environmental drawbacks, that potentially hinder development efforts. Additionally, most existing HPPs have aged and suffer significant mechanical degradation, leading to reduced hydraulic energy generation capabilities [27]. Some of these issues have had repercussions for investment returns, refunds, and regional collaboration. For instance, Ethiopia's construction of the GERD downstream of the BNR prevented Egypt from maintaining its exclusive access to the Nile River. As a result, there was a threat to water security upstream, which raised political and diplomatic tensions between the two nations. These challenges, coupled with economic concerns, resulted in the downscaling of GERD from its originally planned 6,450 MW to 5,150 MW [58,59]. Bonvoisin [60] observed that most nerve-racking aspects are long-term perspectives, which he terms insufficient electricity tariffs, cash flow issues, noncompliance with the financial responsibilities of member states, and administrative deficiencies in projects. Whether these constraints persist and even worsen over time is a matter that requires careful study and decision making. While most constraints result from local incapacitation, such as a lack of finance, skills, and ineffective public policies, environmental challenges spanning global warming, climate change, and land use changes often stem from transboundary and global causes. The solutions to local challenges are known and achievable through regional programs and investment. For example, the technological gap can be addressed through capacity-building programs, innovation promotion, and technology transfer on a global scale. Socioeconomic challenges are often overcome through direct investment and public awareness. Political and policy-based issues can be reassessed and modified to ensure adaptability. On the other hand, addressing environmental issues requires more international collaboration. Out of these challenges, we delved into understanding the degree of change in climatic conditions and potential impacts on hydropower development.

### *Mechanisms of climate change-induced impacts*

Despite the promising future, identifying influencing factors and building resilience against existing and future challenges are needed to ensure the full implementation and operation of the renewable energy potential of SSA. Climate change has intensified and triggered life-threatening and damaging events, thus necessitating the need for resilience building [61]. An increasing pattern of meteorological phenomena is projected to worsen in the mid-century [41]. Therefore, hydrological-dependent infrastructures such as HPPs could be affected, as witnessed at several other SSA HPPs. To assess past relative changes in temperature and precipitation, we analyzed CRU data and found an increasing trend between 2001 and 2020. Despite the increasing trends, there is a contrasting outcome of an evenly distributed change across the region. This mixed spatial distribution of change, the course of change, consequences, and severity differ from one member state to another. These factors are described in the following mechanisms and scenarios.

**Variation in precipitation pattern:** Irregular rainfall patterns impact the quantitative properties of rivers, which may result in drought, flooding, or a shift in the flow of rivers. Drought-induced insufficient flow could lower the hydraulic head, forcing turbine shutdown and HPG capacity downscaling. Conversely, intense rainfall may necessitate load sharing and reservoir modification to offset the excessive inflow; in both ways, if not achievable, this results in flooding, downscaling, and dam failure. For instance, Olaka [62] estimated that precipitation over Lake Victoria in the east will increase by 5-25% (in the eastern and western parts, respectively), while Salami [38] reported that the discharge of Kainji will decrease. Both scenarios indicate that the operation of the existing HPP may be affected.

**The simultaneous rise of temperature and evaporation:** a temperature rise ultimately leads to increasing evaporation [63,64]. A reduction in a river's resource potential due to climate change has hitherto been common in southern and northwestern regions. A significant example is the 10–20% reduction in streamflow expected over West African waters, as estimated by Obahoundje and Diedhiou [34].

Drought extension or desert encroachment: The Sahel and Sahara Deserts are expanding spontaneously due to global warming and climate change [65,66]. This condition maximizes water scarcity for competing demands such as irrigation, hydropower water, and domestic uses in neighboring areas. Even though water stress is increasing, Salman Abdou suggested that effective policy formulation should be used as an instrument to safeguard SSA waters in the future [67].

Shift in the pattern of snow and glacier melt: The volumetric flow of glaciated basins such as the Tana River in Kenya depends on glacier melt and precipitation. CMIP6 projections suggest that rainfall is expected to increase [68], even though an increase in temperature maximizes the rate at which glaciers melt. As a result of these scenarios, vulnerability to floods occurs [69], which could affect dam operation.

Poor water quality: climate change impacts all physical, chemical, and biological properties of water. The intensification of rainfall, floods, and runoff increases the sediment load, while extended dryness and dust storms also increase sedimentation and siltation. These phenomena could decrease a reservoir's capacity, reduce inflow, and affect the function of facilities.

All challenges are grouped as environmental, technological, governance, and socioeconomic factors. Understanding the mechanisms of impact on hydropower development is crucial in guiding future development and planning for sustainability enhancement.

## VI. CONCLUSION

Hydropower in SSA has grown in capacity, but the pace of development is still slow compared to the increasing demand and dependency. The harnessed capacity (35.284 GW) compared to the potential capacity (179.782 GW) is estimated at 19.6%, representing the percentage of HPP developed. The rate of HPP development from 2019 to 2022 is estimated to be 9.7%. Although the potential capacity does not fully represent the total potential capacity of SSA hydropower, it is still a positive indicator of renewable energy development in the region. Additionally, when considering existing and planned capacity, an additional 0.68 GW was observed in 2023, bringing the total harnessed capacity of HPP to 35.928 GW. An observed difference of 1.061 GW exists between the harnessed and existing capacity, which can be attributable to existing HPPs with a capacity lower than 75 MW that are excluded in the GEM's hydropower report. A planned capacity of 12.464 GW is anticipated between 2024 and 2030. While some nations face challenges that hinder extensive development, countries such as Ethiopia, Angola, Tanzania, the DRC, South Africa, and Nigeria are envisioned to benefit significantly from HPP development. Despite the unequal distribution of opportunities for hydropower, the centralization, modernization, and transboundary T&D of energy through the REC objectives of power pool development are considered critical tools for reducing regional energy deficits. However, the existing challenges have necessitated the implementation of rigorous sustainability assessments. Therefore, this review highlighted and discussed noteworthy environmental, socioeconomic, technical, political, and policy-based challenges. It is believed that these challenges have negatively affected the development and sustainability of HPP and will continue in a similar pattern if recovery or adaptive measures are not considered. We delved into understanding the environmental challenges, particularly climate change, by assessing the changes observed in the past two decades. By utilizing spatial temperature and precipitation data gathered from the CRU and applying the interpolation algorithm, we found a 2.42% (0.6 °C) increase in temperature and a 5.97% (49.43 mm) increase in precipitation. These results support those of previous studies, indicating an increasing trend in these parameters with a projected monotonically increasing trend. The mechanisms underlying the impact of climate change on the SSA can be summarized into five categories: (1) variations in precipitation patterns; (2) simultaneous increases in temperature and evaporation; (3) increases in drought or desert encroachment; (4) shifts in snow and glacier melt patterns; and (5) impacts on water quality. Finally, decisions for future development must be made in light of these current scenarios and mechanisms to enhance the sustainability of existing and prospective hydropower infrastructures.

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