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Evaluating climate Change's impact on hydroelectricity in the Zambezi river basin

Kaitano Dube [a,*], Godwell Nhamo [b]

[a] Ecotourism Management, Vaal University of Technology, Andries Potgieter BlvD, Vanderbijlpark, 1911, South Africa
[b] Institute of Corporate Citizenship University of South Africa, Pretoria, South Africa

A R T I C L E I N F O

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A B S T R A C T

This study investigates the effects of climate change on energy security in Africa, specifically focusing on the Upper and Lower Zambezi Basin. Data from the Kariba River basin sub-catchments, annual reports, the Climate Data Store, and Teal Tool Earth's country-by-country climate data were analysed through quantitative and qualitative data analysis techniques. The Mann-Kendal Trend Analysis was used to analyse time series and test the significance of changes to the climate. The historical climate and hydrological data analysis showed evidence of a slight increase in average rainfall amounts in the Zambezi River Basin but with high rainfall variability in some areas. Despite droughts increasing in frequency, there is a general increase in hydrological annual average water flow in the Zambezi River at two of the three sample sites. The increased water flow through the region could be attributed to population growth-induced land clearance and the degradation of wetlands in Angola's highlands. Although there is an increase in hydrological water flow into Kariba, there are water shortages for hydroelectricity generation due to increased generation capacity, resulting in increased demand for more water than in previous years. The unsustainable water abstraction to meet growing energy demands contributes to low water levels in the lake. The study recommends energy diversification and new hydroelectricity where the potential exists in the basin to reduce over-reliance on Lake Kariba with care not to disrupt the basin's hydrology and other economic activities. The study results provide insight into the potential effects of climate change on energy security in Africa.

1. Background and introduction

The Zambezi River, one of Africa's most extensive waterways, holds immense significance for those who reside along its banks. It plays a pivotal role in ensuring their livelihood security, serving as a vital resource for various purposes, including agriculture and fisheries, which are fundamental to the socio-economic well-being of the local communities[1–3]. Moreover, the river is a crucial ecological element in the region, with numerous national parks along its course[4]. As a result, the Zambezi River greatly contributes to the area's economic development by promoting tourism[5,6]. It boasts several prominent tourist destinations, with the Victoria Falls World Heritage Site and Lake Kariba being standout attractions.

Beyond its role in tourism, the Zambezi River is a linchpin in hydroelectric power generation in the region[1]. This electric power is harnessed by some of the most significant power stations along the river, including the Victoria Falls North Bank Power Station, owned

* Corresponding author.
E-mail address: dubekaitano@gmail.com (K. Dube).

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by Zambia, as well as the Kariba North and Kariba South Power Stations, owned by Zambia and Zimbabwe, respectively. Furthermore, the Caborra Bassa Dam Hydroelectric Power Station significantly contributes to the Southern African Power Pool (SAPP). A substantial portion of the region's energy needs are met through the power generated from the Zambezi River, making it a cornerstone of the area's energy infrastructure[7].

Notwithstanding the river's substantial economic significance, there is growing apprehension about the influence of climate change on hydroelectric power generation on a global scale[8]. Many hydroelectric power stations risk experiencing significant adverse effects due to climate change, thereby jeopardising energy security in multiple regions and territories across the globe[9,10]. Recent instances of severe droughts attributed to climate change have caused considerable challenges to renowned tourist destinations such as Victoria Falls[11,12] and Lake Kariba [13] along the Zambezi River.

Recent modelling studies have sought to grasp the potential future of hydroelectric power in the Zambezi Basin due to growing climate change concerns [14]. used an operation model (ResSim) driven by results from stochastic simulations with the watershed hydrology model Pitman/SPATSIM for historical and future climate (Coupled Model Intercomparison Project- CMPI5) scenarios found that hydropower stations were expected to face generation challenges due to water shortages. These investigations have generated various potential outcomes. Using five General Circulation Model (GCM) outputs [15], found that hydroelectricity generation was under threat. These GCMs, however, looked at rainfall and evapotranspiration temperature data without consideration of hydrological flow data to arrive at conclusions where climate historical data was used. This was not representative of the entire basin, making their conclusions inconclusive. The fragmented approach to examining the impact of climate change on hydroelectric generation is a shortcoming that this study seeks to cover.

The region has grappled with intensified energy security issues in the past few years, paralleled by some of the most acute weather extremes like floods, intense droughts, and increasing global and local temperatures[16]. The fact that the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) there is low confidence with regard to the future direction of river flood flow, medium confidence in future increase of aridity and mean precipitation also cast droughts on the extent of reliability and validity of previous studies. While certain sectors link these energy insecurities to climate change, a conclusive study has not confirmed the degree of climate change's impact on the region's energy challenges.

Considering the pivotal importance of energy and energy security to the socio-economic well-being of the region, this study seeks to address this critical research gap. The primary objectives of this research are twofold. Firstly, to investigate the role of climate change in causing energy insecurity in Zambia and Zimbabwe. Secondly, to assess any other potential factors contributing to energy insecurity in these two countries. The central research question that guides this study is: "What is the impact of climate change on energy insecurity in Zambia and Zimbabwe in recent years (2015–2022)? and what other factors, besides climate change, could be responsible for energy insecurity in these nations?"

2. Literature review

As highlighted by various researchers, Africa is confronted with significant energy security issues[17–20]. These challenges manifest in the form of frequent power outages, commonly referred to as load shedding, which exacts a high toll on the socioeconomic well-being of its populace[21–24]. The continent's burgeoning population and expanding economic activities have considerably escalated the demand for energy[25,26].

Most of the existing energy infrastructure in African nations was established before the era of democratic governance. Initially, these facilities catered primarily to the elite and colonial rulers, who represented a minority then. With the advent of democracy, many countries sought to extend energy accessibility to the broader population, including those in rural areas. This expansion led to increased economic growth and modernisation[27,28]. The rapid proliferation of Information and Communications Technology (ICT) infrastructure in various regions of the continent was primarily facilitated by improved access to energy resources.

However, what has been notably lacking in this context is the development of a modernised energy generation infrastructure, particularly in the form of new power stations[29]; Tehero & d'Ivoire, 2021). This dearth of investment in new power generation facilities has brought electricity supply challenges across Africa.

The generation of electricity in Africa is predicted on power stations utilising various energy sources. Coal-fired power plants primarily drive power generation in Africa[30]. The advent of renewable energy has recently seen an increase in the uptake of solar and wind energy[31], although these still constitute a small portion of the energy mix. South Africa is the only country with nuclear energy as part of its energy mix[32,33], with such coming from the 1940 MW Koeberg nuclear power station. According to Ref. [34]; some Island states are also considering tapping into geothermal to reduce heavy reliance on fossil fuels. In essence, many African economies rely on fossil fuels, which [35] indicate has been central to providing a stable and dependable energy supply for economic development worldwide.

The continent's heavy dependence on fossil fuels and hydroelectricity is problematic in many respects. Fossil fuels such as coal are blamed for contributing to carbon emissions that cause climate change[36,37]. Consequently, there have been growing calls for the continent to abandon fossil fuels and transition towards a carbon-neutral path invested in renewable energy. These calls were particularly loud during the United Nations Framework Convention on Climate Change's 26th and 27th Conference of Parties held in Glasgow, England and Sharm El Sheikh, Egypt[38]. The two COPs took place in 2021 and 2022, respectively. Coal has been particularly singled out for phasing out during COP26[39]. Such a transition is being punted to offer numerous benefits, among them a reduction in carbon emissions, which ensures that the world meets its goal of staying below the 1.5 °C temperature mark and also deals with health challenges associated with coal pollution in Africa[40,41].

The transition from coal presents challenges for Africa, given the central role coal mining plays in the continent's energy value chain. There have been concerns over stranded assets should Africa stop coal extraction. The move will leave millions of jobs sustained by the coal industry being lost. There are also fears that Africa's development will be stifled if the continent moves away from coal without a reliable base load [8]. argued that a reliable base load is critical in energy supply. The question of who bears the cost of such a transition has been at the top of the debate.

Hydroelectricity is the second most significant energy source in Sub-Saharan Africa[42]. Hydroelectricity is one of the preferred energy sources as it falls under the category of renewable energy. However, climate change threatens this energy source[13,43]. Hydroelectricity generation and supply are highly sensitive to weather extremes such as drought[42].

Several General Circle Models have been presented to try and predict the future of energy supply and security under climate change [44]. [45] used climate and integrated assessment models to assess energy security under climate change. However, knowledge gaps still exist concerning how those models are fairing in accurately predicting energy supply to the region[43]. According to Ref. [8]; predicting and modelling climate change impacts on hydroelectricity is complex and challenging. Therefore, monitoring the impacts of climate change on the energy supply is critical to inform users and policymakers, given the centrality of energy to socioeconomic development. This study explores the role played by climate change and socio-political dimensions on hydroelectricity supply systems along the Zambezi River with a particular focus on recent hydroelectricity generation at Kariba North (Zambia) and South (Zimbabwe) Power Stations between 2015 and 2023. This period coincides with an episode where the region has been experiencing high load-shedding levels, making it a period of research interest.

2.1. Study area

The study explored the Upper and Lower Zambezi Basin data (Fig. 1) to understand the precipitation patterns. The Zambezi River network cuts across several countries and has two major dams critical to hydroelectricity generation in the Southern African Development Community (SADC). The Zambezi basin has a significant share of the 24 % hydroelectricity generation contribution to the Southern African Power Pool (SAPP)[46]. The basin stretches over several countries covering 1.3 million km, including Angola (18.2 %), Zambia (40.7 %), Zimbabwe (18 %), Malawi (7.7 %), Tanzania (2 %), Botswana (2.8 %), Namibia (1.2 %) and Mozambique (11.4 %) [47]. About 33 % of the population of these countries live in the Zambezi Basin (Ibid). The river is 2,574 km long and empties its water into the Indian Ocean in Mozambique. Major dams on the river include Kariba (shared between Zambia and Zimbabwe) and Cahora Bassa Dam. The Zambezi River is susceptible to rainfall changes and the impacts of climate change[11,48]. This affects tourism and energy security from time to time, particularly the Kariba North and South Power stations in Zambia and Zimbabwe, respectively [13].

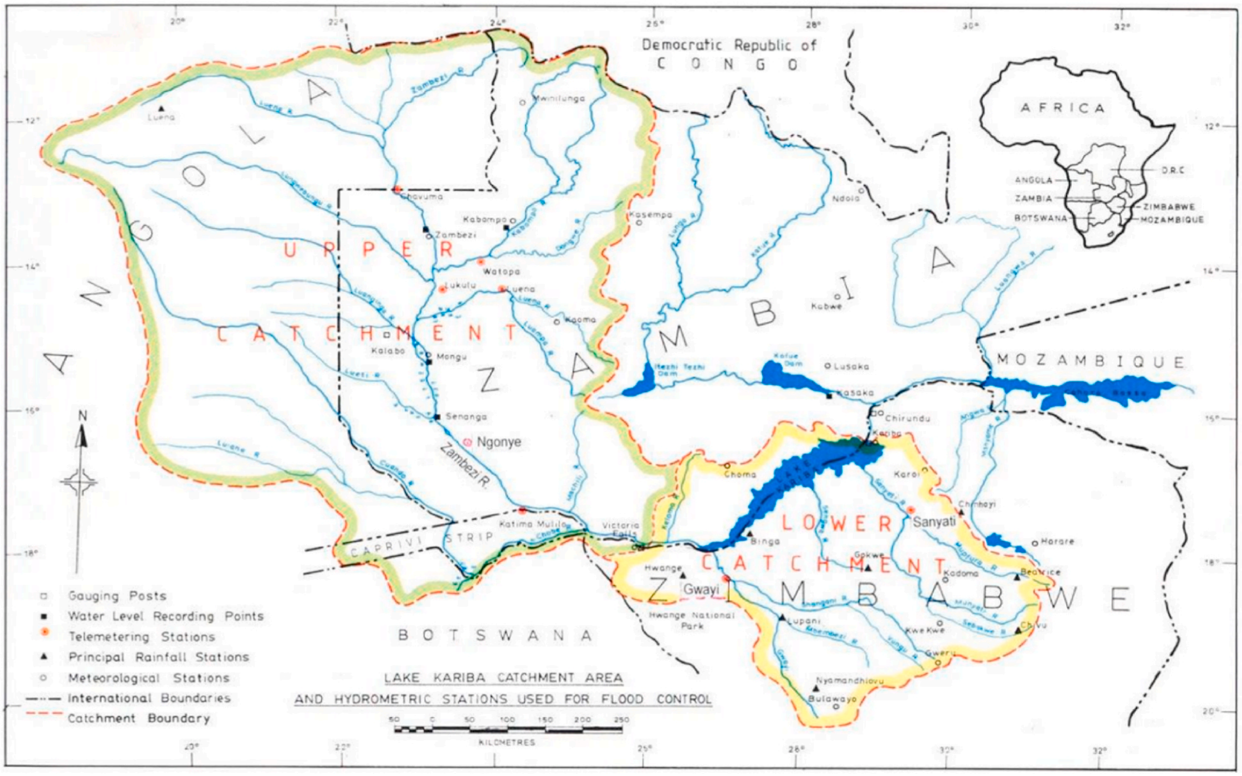

Fig. 1. Location of the Zambezi River and its tributaries: Source Zambezi River Authority (2023).

2.2. Study methods

The study makes use of climate data that was obtained from Teal Tool Earth. Teal Tool Earth is a product of the World Energy and Meteorology Council (WEMC). The Tool provides climate data map visualisations with data sets from as far back as 1950. This study explored data sets between 1979 and 2022, focusing on temperature and rainfall data in the Zambezi Basin that feeds into Lake Kariba. The global map tool provides country-by-country climate data and sub-country data. The Tool provides access and uses climate data. The Tool utilises data from ERA5, a Copernicus Climate Change Service (C3S) Climate Data Store. The ERA5 taps from large historical data sets, which rely on estimates based on modelling and data assimilations. Historical data for the studied period is available from the Climate Data Store (CDS) and is quality-assured. This data can be relied on for such studies as this one. ERA5 also provides data gathered from hourly estimates, relies on grids of a 30 km grid, and resolves the atmosphere using 137 levels up to 80 km from the surface. The data set has been used by the World Meteorological Organization (WMO) and used to populate models used in General Circulation whose results appear in Intergovernmental Panel on Climate Change (IPCC) assessment reports.

In addition to that main data set, hydrological data from the Zambezi River Authority was also explored. Zambezi River Authority is tasked with managing the water resources in the Zambezi River for electricity generation. While the authority was established in 1987, its work started in 1964 [49]. The authority has a network of 13 hydrological stations that collect water flow data at various points of the Zambezi River (Ibid). Zambesi River Authority also measures daily Lake levels for the Kariba Dam. It also allocates water to the two power stations of Kariba North and South Power Stations in Zambia and Zimbabwe, respectively. It monitors water in Lake Kariba daily, measuring inflow lake levels, and one of the components it measures is evaporation rates in the lake, amongst others. In this study, given that some hydrological stations are new while others are old, data from 1976 to 2022 was scrutinised, and the times will be reflected on each graph. Zambezi River Authority is an authoritative source for hydrological data service provision and has been used in several studies[13,50,51].

Precisely for this study, data for various basin tributaries were gathered and analysed to ascertain climatic trends, which could have contributed to the shortage of water inflows into Lake Kariba over the years. As such, data from the sub-catchments of the Kariba River basin are analysed to understand historical developments in the basin to try and understand the climate development and map their observed and potential risk to energy security in primarily Zimbabwe, Zambia and Southern African Power Pool (SAPP) given the interconnectedness of the grid system.

The study also utilised data from annual reports for Zimbabwe Power Company, Zambia Power Company, Zambezi River Authority and other authoritative data sources between 2015 and 2023 to arrive at conclusions (Table 1).

Data analysis borrowed from quantitative and qualitative data analysis techniques. The qualitative data followed a content and thematic analysis of secondary data sources such as annual reports. The sense-making of the available data from secondary sources followed a comprehensive study of secondary data. The approach was found to be inexpensive but afforded the researcher to gain insight into the study's objectives and critical research questions. Where needed, data was rerecorded to formulate tables and graphs using Microsoft Excel.

Regarding climate and hydrological data, it was analysed using Mann Kendal Trend Analysis to analyse the time series and test the significance of changes to the climate. Trend analysis was run on Microsoft Excel Sheet on XLSTAT version 2023.1.1 (1401). The significance level was set at 5 %, and the confidence interval was set at 95 %. This is a default setting for the test. The following approach is applied regarding climate data: If the computed p-value is lower than the significance level alpha = 0,05, one should reject the null hypothesis H0 (no trend in the series) and accept the alternative hypothesis Ha (there is a trend in the series). Mann Kendal Trend Test is highly used in detecting monotonic trends in hydrometeorological time series[52,53].

3. Results and discussion

The results section presents a meteorological and hydrological analysis of developments between 1979 and 2021. The study will start by examining the meteorological trends to ascertain how rainfall trends affected the hydrological system of the basin that feeds into the Kariba Dam.

Table 1
Data sources used in the study.

Data	Source	Information
Archival Data	•Hydrological data from the Zambezi River Authority •Meteorological Data from Teal Tool •Meteorological Data from Data Access Viewer	•Waterflow at selected points along Zambezi River, water losses •Rainfall data •Temperature data
Secondary Data	•Zimbabwe Power Company Annual Reports 2015–2021 •Zambia Energy Supply Company (ZESCO) Annual Reports 2015 to 2022 •Zambezi River Authority Annual Reports 2015 to 2021	Reports were interrogated to obtain information on water allocated for power generation vs water utilised for electricity generation.
Other Data Sources	•Reputable News Paper Articles •Electricity company websites •Other relevant sources	•Impact and narratives on load shedding •Generation Statistics

3.1. Meteorological trends in the Zambezi Basin

One of the major areas where the Zambezi gets its water, which ends in the Kariba Dam, is the Northwestern part of Zambia. Other parts contributing to Kariba's water include the Western Part of Zambia stretching to North East parts of Angola and the East and Central East part of Angola to the Caprivi Strip and the North Western Parts of Zimbabwe (See Fig. 1). The following section is going to provide sample data for these regions.

Fig. 2 shows the rainfall pattern in one of the source regions for water that flows into Zambia. The Chavuma stations in the Northwest part of Zambia account for the highest water flow into Lake Kariba. The Northwest region had yet to witness significant changes in rainfall between 1979 and 2021. Over the 43 years under study, the area's average annual rainfall has been 1233 mm, with the recorded maximum rainfall being 1501 mm (recorded in 2021) and the lowest rainfall recorded being 994 mm (recorded in 2005). The standard deviation for this province is comparatively lower than that of other stations, standing at 102.7. Although there are several years where annual rain falls below the average, there is no considerable variation from the mean. A slight increase in annual rainfall is detected over the area, which is not statistically significant, as shown in Fig. 2. Over the past five years, three years of rainfall fell below the average, including in 2021, where the annual rainfall total was 1178 against the expected annual average of 1233 mm. If one considers the standard variation, the variation is not that huge.

The Western Province of Zambia's average yearly rainfall is about 952 mm. The area's observed maximum rainfall was about 1283 mm, recorded in 2008, and the minimum recorded rainfall was 664 mm, falling in 1995. In the same year, the North West Region of Zambia recorded its lowest rainfall amount. The standard deviation of rainfall in the area is 140.5, with rainfall variation way higher than in the Western Province. The region generally has seen an increase in total annual rainfall amounts, which is statistically significant. Rainfall increased from an average of about 900 mm to slightly above 1000 mm annual rainfall. This is despite huge annual variations, which have seen some of the highest and lowest rainfall events in the last five years. The second highest and second lowest were recorded in 2020 and 2019, respectively.

On the Angolan side of the basin in Moxico, the total annual average rainfall is 1282 mm. Maximum rainfall was 1584 mm, reported in 2020, while the lowest rainfall was 1076 mm, observed in 1995 mm (Fig. 3). The standard deviation for the region is 121.971. The annual variation is low, with most years tending to have rainfall falling around the mean serve for a few years. The trend shows that there has not been much change in the area's rainfall. There is, however, a slight decrease in the rainfall amount, although this is statistically insignificant. The Cuando Cubango receive an annual average rainfall totalling 890 mm, a maximum of 1222 mm, which was received in 2008 and a minimum of 615 mm reported in 2015. In 2019, the area received its second-lowest rainfall of 625 mm. Although the trend shows an increased rainfall amount, this is probably caused by the large upswings recorded in some years. Such rainfall increases could affect environmental responses in the ecosystem and river hydrology.

The Caprivi strip receives an average annual total rainfall of 693 mm. The area received a maximum of 1008 mm in 2008, while a minimum of 455 mm was recorded in 2015. The standard deviation of 140.936 indicates a higher deviation and annual rainfall variability in the region. Between 2015 and 2021, rainfall in the Caprivi strip has been highly variable. The rainfall trend shows that there has been a statistically significant increase in the annual rainfall received in the area (Fig. 4). Rainfall has been highly variable in the lower catchment in Matabeleland North in Zimbabwe. Evidence shows that annual rainfall in the area has significantly increased between 1979 from an average of about 600 mm to close to 773 mm. The total annual average is 682 mm. The lowest rainfall was received in 2002 when 415 mm of rainfall was received, while the highest was recorded in 2017 when about 994 mm was received.

By and large, the study showed that the basin, in general, has witnessed an increase in annual rainfall receipts, albeit high rainfall variability in some other areas. The trend is that of a basin witnessing increased total rainfall amounts. This contradicts the [54]; which observed a high-confidence decline in precipitation but, most importantly, points to the unreliability of depending on GCM model data, which tends to generalise the picture of climatic patterns. The climate tends to vary over smaller geographic regions. This could be due

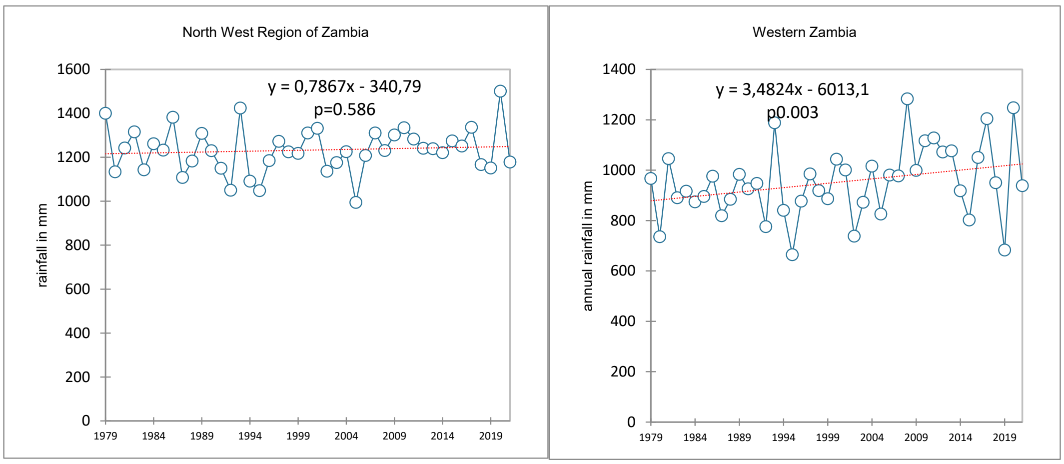

Fig. 2. Rainfall pattern over the Zambian part of the Zambezi River Basin, which feeds into Kariba Dam.

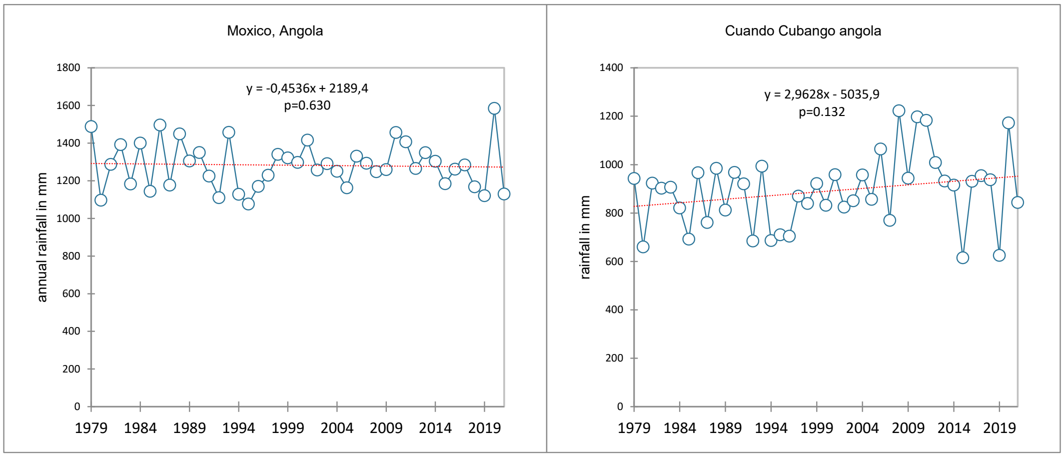

Fig. 3. Rainfall in the Angolan part of the Zambezi basin feeding into Kariba.

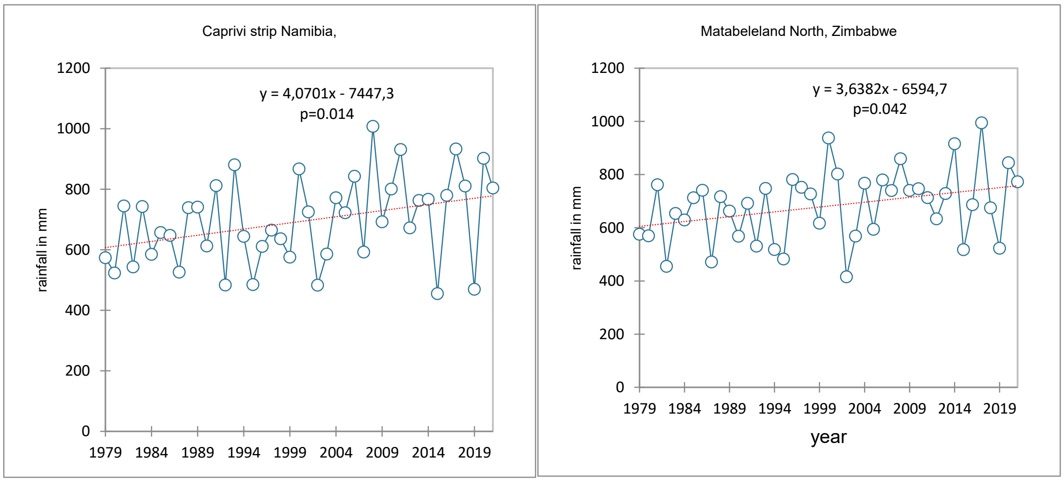

Fig. 4. Rainfall pattern in Caprivi Strip region and Zimbabwe's Matabeleland North province 19179-2021.

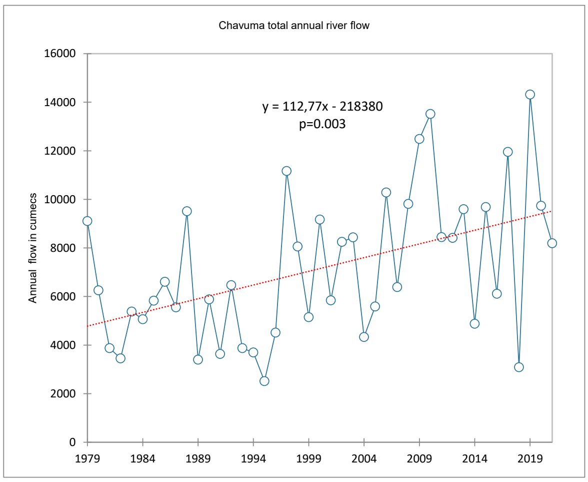

Fig. 5. Annual River flow at Chavuma station.

to the IPCC using a much longer data set or an analysis of a larger geographic area, which tends to mask the micro conditions. However, the findings of this study confirm earlier findings by Ref. [12]; who observed a general increase in rainfall over the Victoria Falls area, which falls under Matabeleland North, whose results compare favourably with the findings of this study. There is no doubt that given that this data relied on relatively large areas, microclimatic conditions could see other areas receiving much less rainfall or a declining trend in rainfall.

3.1.1. Hydrological trends

The study utilised data from three hydrological stations: Chavuma, Ngonye Sioma Falls and Victoria Falls. Evidence shows that there has been a significant increase in water flowing through the station in the northern part of Angola, Moxico, over the study period (Fig. 5). The area shows that rainfall has not increased but has remained the same over the years, with a very slight decline on average (see Fig. 3). Given that the area shares a border with the Northern Zambia area, where a slight increase in rainfall has been witnessed, one cannot rule out there could be a localised increase contributing to the increase in water flow. The growth in population in Southern Africa has also resulted in changes in basin characteristics, primarily through land clearance. Land clearance has a chance of increasing runoff, which could alter the hydrological behaviour of the river. There are well-documented challenges of deforestation in Zambia, for example[55–57]. The degradation of wetlands in Angola's highland areas[58,59], which form part of the Zambezi basin, also affects water flow patterns. More degraded peatlands mean increased water flow in the basin. Increased runoff also threatens the system and ecosystem that typically receives yearly rainfall. Tourism operations and fishing operations seasonality might be disrupted.

The high standard deviation of 3561.716 is a testament to high annual variability in the river flow regime, which could be evidence of episodic flooding and drying of the system. Over the last 43 years, the highest water flow was witnessed in 2019, with a water flow of 14318 $m3s-^{1}$ after what seemed to be a hydrological drought in 2018, which saw 3088 $m^3s^{-1.}$ Such a huge variation shows that the system is vulnerable to high swings, which could mean water insecurity.

Ngonye is a new station established to measure the water flow from Northwest and west of Zambia and East and North of Angola, almost midway through the Zambezi upper catchment. The station is located in Southern Zambia (Fig. 6). The study found that the water flow has been variable over the past few years (2015–2021). The lowest flow was witnessed in 2018, with the general trend showing that the water flows at the waterfall primarily serve Zambia's domestic tourism market. The year 2018 marked the height of one of the most prolonged drought episodes in Southern Africa, which some scholars argue was amplified by climate change[60,61].

One of the most important stations in this study is the Victoria Falls station, located a few meters from the Victoria Falls World Heritage Site. Most water that passes through Victoria Falls comes from the bulk of the rainfall regions and hydrological stations covered earlier, ending in Kariba Dam. The study found that there is a general increase in the water flow at Victoria Falls (Fig. 7), which is statistically significant in terms of the total volume of water that flows through the station from an annual average of less than 10 000 $m3s^{-1}$ annually to about 15 000$m3s^{-1}$ which is an increase in the annual volume of water that flows into the dam. The long-term mean water flow at Victoria Falls is about 12 283 $m3s^{-1,}$ while the highest recorded water flow during the study period is 20 426.5 $m3s^{-1}$. This was recorded in 2010, the second-highest recorded water flow in 2011 and the 3rd highest in 2018. The lowest water flows were recorded in 1996, when only 4683$m3s^{-1}$ was observed. There is a high standard deviation of water flow at Victoria Falls. The highest annual variation is perhaps witnessed between 2019 and 2020, indicating a hydrological drought. This hydrological drought sparked fear and outrage about the 'drying up of Victoria Falls as water levels dipped significantly in late 2020. This high annual variability worries water and energy security sustainability in the Kariba Dam and Kariba North and South Power stations.

The study also examined evaporation's role in Lake Kariba's water levels. It emerged that in as much as the temperature is touted to have increased in the region, the average evaporation rates over Lake Kariba have remained mainly unchanged over time, although with annual fluctuations (Fig. 8). On an annual basis, the dam loses, on average, 8494 million cubic million litres of water. In the first half of the study period, the annual average was 8397 million cubic litres, against 8578 in the last half. The increase and loss of water to

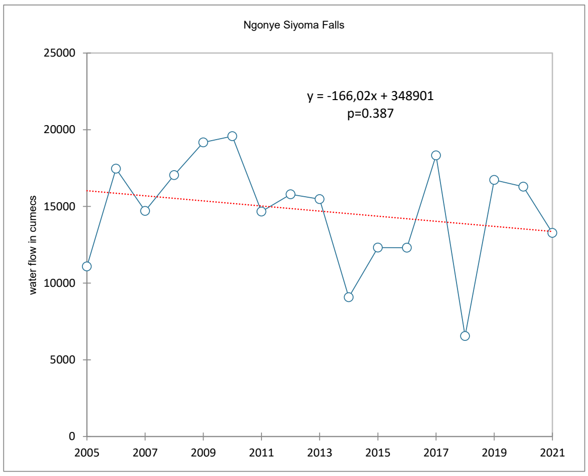

Fig. 6. Ngonye water flow regime between 2005 and 2021.

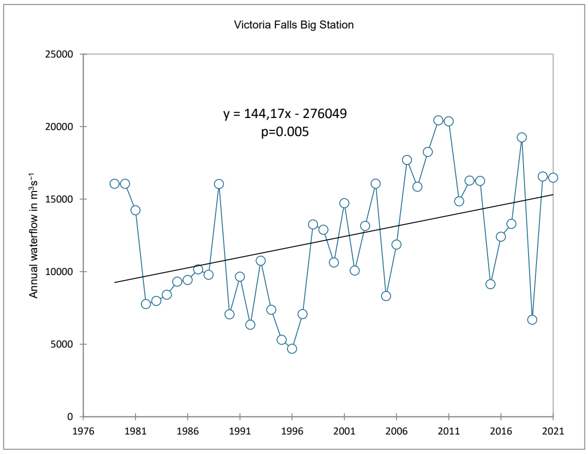

Fig. 7. Hydrological flows over Victoria Falls between 1979 and 2021.

evaporation could be attributed to vegetation changes in the basin and an increase in temperature over the years.

The study found that the annual average maximum temperature over Lake Kariba has increased over the period, although the increase falls short of being considered statistically significant. The temperature over Lake Kariba increased from about 40.9 °C to slightly above 42 °C (Fig. 9). It is important to note that although most months witnessed a temperature increase, the increase was not statistically significant except for October, which increased from about 40.1 °C to about 41.7 °C. (y = 0,0395x - 38 244 p-0.038). This increase, if it continues, can have an impact on the evaporation rates over Lake Kariba. There is a potential for increased water loss to evaporation over the dam, reducing the amount of available water for turbine flows.

3.1.2. Energy supply challenges within the region

The past couple of years have been particularly challenging for the region from an energy perspective. The energy shortfall has been heightened over the past two years post the COVID-19 pandemic between 2022 and 2023.

4. Discussion

The study found that the evidence of climate variability and change manifests in the form of highly variable annual hydrological flow and rainfall in the Zambezi Basin. Nonetheless, the general pattern shows an increase in the total amount of rainfall in most parts of the basin amidst high annual variability. In four out of five rainfall regions sampled in Zambia, Angola, Namibia, Botswana and Zimbabwe, the general pattern is increasing rainfall between 1979 and 2022. During that period, only one rainfall region showed a slight decline. A look at hydrology reveals that there has been an increase in river water flow at the Chavuma Station and the Victoria Falls Station and a slight decrease at the Ngonye Siyoma stations. Regarding the hydrological pattern, the data confirms the findings of historical data at Victoria Falls hydrological station, which revealed an increase in river water flow[12]. Historical rainfall data has

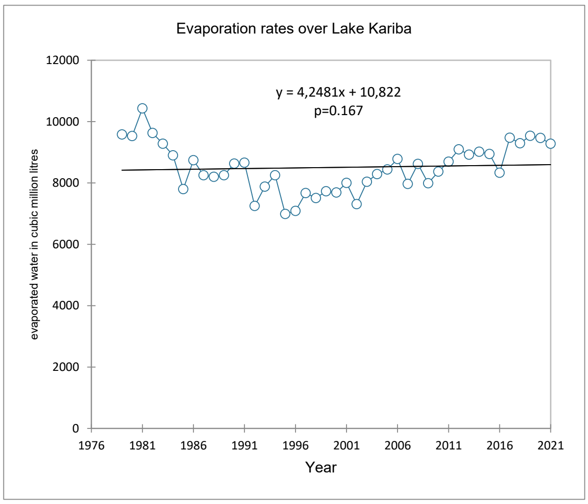

Fig. 8. Evaporation rates over Lake Kariba area 1976–2022.

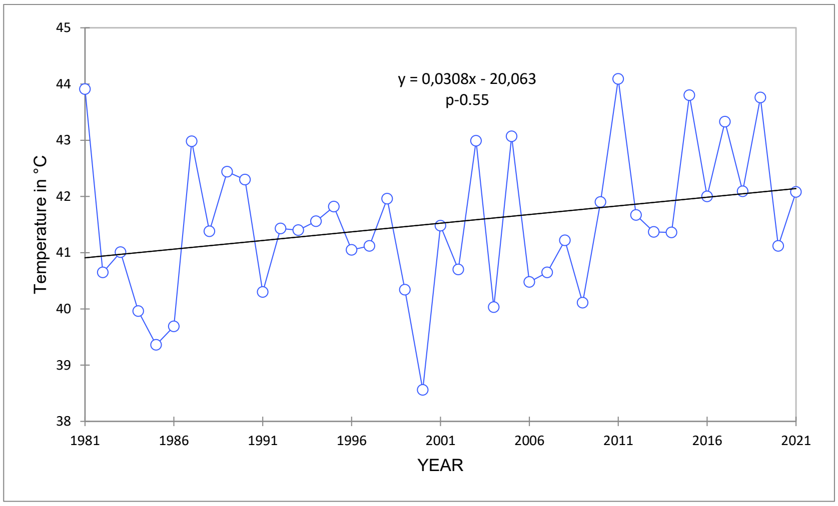

Fig. 9. Annual Average maximum temperature over Lake Kariba.

been based on individual rainfall stations, which presented a diverging picture in the region, with some stations showing a decrease in average annual rainfall see Ref. [15] on Mwinilunga and Kaoma rainfall stations [11]; on the Livingstone rainfall station and also [13] on Kariba rainfall stations. Needless to say, in some of these stations, the decrease was very slight and statistically insignificant. In Victoria Falls, annual rainfall increased, albeit with increased drought frequencies[12].

The annual variability can be a cause for concern in some years as the variability of the patterns can be quite sharp, which might threaten water security. What is emerging, nonetheless, is that the total water flow into the Kariba reservoir has increased over the years. This should work in favour of electricity generation in the main. Evaporation has not significantly increased so much that it compromises electricity generation capacity. Therefore, the recent uproar over the electricity shortage can partly be blamed on other factors, as climate variability does not seem to have had a profound impact.

What is clear from the study is that there has been a statistically significant turbine outflow over the years, which points to an increased water allocation for hydroelectricity usage from Lake Kariba (Fig. 10). A similar observation was made by Ref. [13]; who observed a higher amount than actually allocated water to drive turbines at Kariba North and South in some years. This points to increased water usage at Kariba North and South Power stations. This could be attributed to the increased demand for electricity to power the growing population and economic and social activities in Zimbabwe and Zambia. In March 2018, the Kariba South Power Station was expanded by two units with 150 MW capacity each, raising the installed capacity to 1050 MW, making it Zimbabwe's largest power station[62]. While the initial capacity for Kariba North Power Station was 600 MW, the station was upgraded between 2002 and 2014 to 1080 MW. The time and completion of additional units seem to coincide with some of the severe power outages in the two countries, which might point to the level of contribution of increased water for generation and power outages in the region. Before the expansion projects at Kariba North and South Power Station, the outflow was partially attributed to the opening up of the floodgates, which is now a rare occasion[13]. Given the hydrological and rainfall patterns, one would expect more floodgate openings.

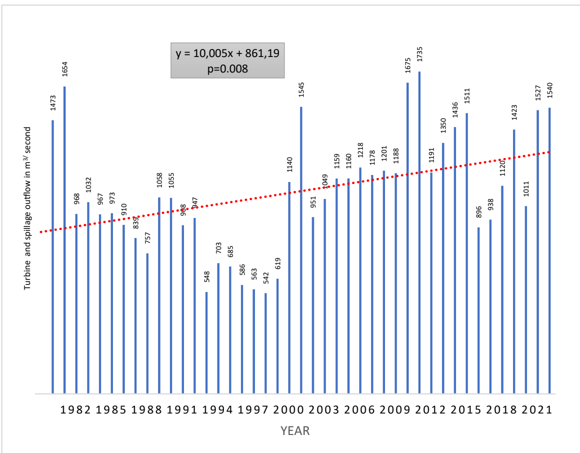

Fig. 10. Turbine and spillage outflow at Lake Kariba.

The increased abstraction means more water is being utilised for generation. Hence, water levels are kept at low levels, inhibiting the opening of the floodgates. The expansion of power generation capacity resulted in a mismatch between water supply and demand. Consequently, this mismatch creates the forced water supply curtailment, reducing the two countries' generation capacity and electricity.

During the peak of the power outages that affected Zimbabwe and Zambia, it became apparent that both countries may have disregarded the water allocation quotas set by the Zambezi River Authority. ZESCO's annual report for 2020 acknowledged that they had maintained Kariba's power availability factor by surpassing their annual allocated water usage by 157 %. In 2019, ZESCO exceeded their water allocation from the Zambezi River Authority by 110 %[63].

In 2018 and 2017, ZESCO had not fully utilised their water allocation, operating at −5% and −6.9 % of the allocated water, respectively. In 2016, ZESCO exceeded its water allocation by 5.584 million cubic meters, which they recognised as a potential threat to the water resources in the dam[64]. In 2015, ZESCO could not use its allocated water due to the El Niño-induced drought that had affected the region.

On the Zimbabwean side, the Zimbabwe Power Company noted that they had exceeded the 22.5 billion cubic meters of water allocated by the Zambezi River Authority. However, they had significantly surpassed their allocation to compensate for the poor availability factor from coal-fired power stations in the last quarter of 2022, which led to water challenges in Lake Kariba[65].

The records reveal that while extreme weather events linked to climate change are a concern, the ongoing issue of water over-utilisation is a significant challenge. Back in 2015, the Zambezi River Authority adjusted its water allocation, reducing it from 45 billion cubic litres to 40.5 billion due to the drought induced by El Nino. Despite this reduction, the two power stations consumed a staggering 43 831.48 billion cubic litres of water, which exceeded the revised allocation by 8 %[66].

Subsequently, in 2019, power generation companies surpassed their allocated water usage by 5.95 %. In 2020, they exceeded their water allocation by a substantial 36.78 %. By 2021, power utilities utilised 49.7 billion cubic meters, marking an 11 % increase from the previous year. Consequently, the power generation companies faced a penalty of US$ 12.098 million imposed by the Zambezi River Authority[67].

Political leaders are increasingly pressured to demonstrate improved performance in energy security, a topic that has taken on significant political significance[68]. Despite the evidence indicating a growing percentage of the population gaining access to energy, there remains a challenge in matching the energy generation capacity to this growth (as illustrated in Fig. 11). Notably, Zimbabwe and Zambia have witnessed a remarkable rise in the number of people with access to electricity, surging from less than 20 % in 1992 to nearly 50 % in 2020. Historically, countries like Zimbabwe have relied on imports from neighbouring nations such as South Africa and Mozambique to meet their energy needs. However, South Africa's power utility, Eskom, grapples with its own issues, including heightened energy demand, corruption, and a shortage of technical expertise[69], which limits its ability to support the energy requirements of its neighbouring countries readily.

Given the economic aspirations of the continent and the percentage of people who still lack access to energy in Zambia and Zimbabwe, the pressure and demand are likely to increase. Alternative energy sources must be sought, and hydroelectric power stations must be managed sustainably to ensure sustainable energy security. Even though Zimbabwe Electricity Supply Authority (ZESA) has an installed capacity of 2412 MW and ZESCO has 2891 MW as of 2020, the countries failed to generate at their capacity with Zimbabwe Elect ZESA. Operating at 1400 MW and ZESCO managing 2736 (Southern [70]. This was against a peak demand of 1724 MW for Zimbabwe and 2510 for Zambia (Ibid). This means the two countries failed to meet their energy peak demand. The situation further deteriorated in 2022 when water level dropped in Lake Kariba, which resulted in the Zambezi River Authority drastically cutting the amount of water that is allocated towards generation to the 2 energy companies. This forced prolonged load shedding that stretched between 12 and 18 h daily.

In Zimbabwe, the ageing coal-powered stations such as Hwange have resulted in lower energy availability and worsening pressure on hydroelectric power generation stations. Evidence shows that although the Hwange power station has an installed capacity of 920W [62], it has lately been generating as little as 75 MW (as of March 2023), which puts pressure on the much more reliable Kariba Power station. Other coal-fired power stations like Munyati and Bulawayo are not operational or producing electricity. Harare power station produces 11 MW, a small fraction of its operational capacity (Ibid).

In light of the growing challenges and demand for energy, there is a need for the two countries to leverage the existing potential for water optimisation by establishing more hydroelectricity generation units. Several potential hydroelectricity projects along the Zambezi River require funding. Private-public partnerships can be utilised to ensure that national and regional energy aspirations are met.

5. Conclusion and Recommendations

The study found that climate change is a real phenomenon within the Zambezi River basin and causes high annual rainfall variability and river water flow. The study notes that out of the five rainfall regions in the basin, only one region shows a slight decline in annual rainfall amount regardless of increased drought occurrence. These findings tally somewhat with hydrological waterfowl data, which shows an increase in total water flow at 2 of the 3 river gauging stations. The increase of water flow at Victoria Falls gauging stations is important, as water is a significant indicator of water that ends up in Lake Kariba.

There is clear evidence of intense rainfall activities in the basin, accounting for high regional interannual variability. There are years of extreme drought and very high rainfall events within the basin, which could threaten energy security in the future if water resources are not managed well. The general trend is that there have been more water flow within the basin than before, which should border well for hydroelectricity generation. This can be done most of the time with sustainable management of the available water

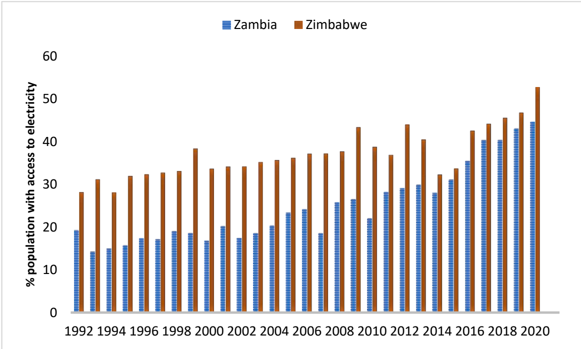

Fig. 11. Percentage of the population with access to electricity in Zambia, Zimbabwe and South Africa (Source: Authors, Data from the World Bank 2020).

resources. The major water supply challenges at Lake Kariba are largely due to the unsustainable use of the available water resources. The surpassing of allocated water quarters from the Zambezi River Authority by the two power generation companies, namely Zimbabwe Power Company and ZESCO, is at the heart of recent energy security challenges. The situation has been compounded by ageing coal-fired power station infrastructure, poor forecasting of energy demands, and lack of adequate planning to cater for the same.

There is clear evidence that governments are failing to match energy demands to energy infrastructure development, which is a challenge in many respects. The culture has shifted the blame towards climate change, with very few solutions being offered. Scapegoating climate change for the poor management of water resources inhibits the adoption of solutions to the energy challenge.

Given that there is a growing population and economies and energy demand, there is a need to invest in power generation of various typologies, including wind, solar, nuclear and green hydrogen and move away from over-reliance on hydropower generation by the region as a strategy to achieve energy security in the medium to long term. Governments also need to deal with the challenge of climate change and energy security honestly to ensure trust with the citizens of member states. Transitioning to alternative energy sources is an environmental necessity and an economic opportunity. This comprehensive strategy, encompassing skills and technological transfer, increased financial support, and providing incentives, is paramount for fostering sustainable development. Tax rebates can be used as a powerful tool for fiscal relief, and incentivisation holds the potential to catalyse this transformative shift. This will require governments, businesses, and civil society's concerted efforts to achieve a cleaner, more sustainable energy future.

The need to ensure that the construction and development within the region must consider the need for energy efficiency can never be over-emphasised. Regarding ensuring energy efficiency, the government needs to adopt policies and strategies aimed at upscaling the construction and designing of green building design. On the other hand, investment in efficient lighting and promoting star-rated energy-efficient appliances for homes and industry is critical in ensuring energy efficiency. The government can also assist in putting in place legislation that encourages energy audits and usage of energy-efficient equipment across various industry sectors. The governments can also assist with conducting research and public awareness campaigns and education on energy efficiency and investment in renewables such as solar and other forms of energy at the industry and household level. As is the current situation, energy efficiency needs to be embedded within communities to ensure that the economies are not energy- and carbon-intensive.

Future research will need to focus on modelling a combination of climate variables with a view to gaining a holistic understanding of the future of energy security in the region. A basin approach should be taken in these studies if they are to be viable. The introduction of new hydroelectric must be monitored to ascertain their impacts on current power stations in future studies.

5.1. Study Limitations

Power generation relies on several variables, such as government policy, which this study has not considered. The study did not also look at current future climate scenarios to ascertain what could be the future due to a shortage of downscaled data at a good resolution. [71,72].

CRediT authorship contribution statement

Kaitano Dube: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Godwell Nhamo:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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