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Presented by

DONNATA ALUPOT

ASSESSING THE IMPACTS OF CLIMATE VARIABILITY ON ELECTRICTY CONSUMPTION IN UGANDA

Defended on 22/04/2024 Before the Following Committee:

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DECLARATION

I, Donnata Alupot, hereby declare that this thesis titled “Assessing the impacts of climate change on electricity consumption, Uganda” is my original work to the best of my knowledge and has not been submitted to the University or any other institute or published earlier for the award of any degree or diploma. I also declare that all the information, materials and results from other works presented in this thesis have been duly cited and recognized as required of academic rules and ethics.

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I, Prof Amos T. Kabo-Bah, hereby declare that I supervised the preparation of this Master thesis submitted therein in accordance with the guidelines on supervision of Master thesis laid down by the Pan African University Institute for Water and Energy Sciences (including climate change), Algeria.

Name: Prof Amos T. Kabo-Bah

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DEDICATION

I dedicate this work to the Almighty God, whose grace has bestowed upon me the life and wisdom necessary to undertake this study. Additionally, I extend my heartfelt dedication to my beloved parents, Okobo Charles and Mutonyi Margaret, whose unwavering love, support, and encouragement have been my guiding light throughout this journey. To my sister, Akwatum Jolly Linus, I express gratitude for her invaluable contributions during the course of this program. Finally, I dedicate this work to my friends and classmates for all the support we shared.

STATEMENT OF THE AUTHOR

By my signature below, I declare that this thesis/dissertation is my work. I have followed all ethical principles of scholarship in the preparation, data collection, data analysis, and completion of this thesis. I have given all scholarly matter recognition through accurate citations and references. I affirm that I have cited and referenced all sources used in this document. I have made every effort to avoid plagiarism. I submit this document in partial fulfillment of the requirement for a Masters in Climate change degree from Pan African University Institute for Water and Energy Science (including Climate change). The dean of the academic unit may grant permission for extended quotations or reproduction of this document. In all other instances, however, the author must grant permission.

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LIST OF ABBREVIATIONS

CEC	Commercial Electricity Consumption
DEC	Domestic Electricity Consumption
ERA	Electricity Regulatory Authority
GCM	Global climate model
GDP	Gross Domestic Product
IEC	Industrial Electricity Consumption
MME	Multi Model Ensemble
RCA4	Rossby Centre regional Atmospheric model (version 4)
RCM	Regional Climate model
SSP	Shared Socioeconomic Pathway
UBOS	Uganda Bureau of Statistics
UNMA	Uganda National Meteorological Authority
WDI	World Development Indicators

ABSTRACT

Climate change is a critical global issue affecting various sectors including the energy sector. Variations in climate can significantly impact electricity markets affecting hydropower generation and thermoelectric plants. These fluctuations can potentially increase outages, highlighting the necessity for informed policymaking and sustainable infrastructure. In this regard, the impacts of climate variability on electricity consumption in Uganda were evaluated from climatic conditions for the baseline period (2008 – 2022) and future period (2023 – 2060) under SSP 2.6 and SSP 8.5 scenarios. Climate variables such as average temperature, rainfall and relative humidity were used for the baseline period, as well as GDP to represent the socioeconomic variable. Future climate projections from the mean of three RCM models downscaled by RCA4 were used in simulating future temperature scenarios. The study utilized the Mann Kendall trend test for trend analysis and significance of the datasets. A multiple linear regression (MLR) model was then employed to assess the current and future relationship between climate variability and electricity consumption in three sectors: domestic, commercial, and industrial. The MLR models were evaluated using Mean Absolute Percentage error and coefficient of determination (R2). The MLR model with temperature and GDP variables performs better than the model of only climate variables with R2 equal to 89.3%, 85.5% and 48.2%, for domestic, commercial and industrial electricity consumption respectively.

The findings indicate that during the baseline period, temperature had a more significant positive influence on electricity consumption when compared to rainfall and relative humidity. Future projections suggest a temperature increase under both SSP 2.6 and 8.5 scenarios, which is expected to positively impact electricity consumption, particularly in the domestic and commercial sectors. Higher electricity consumption is projected for both the near future (2023 – 2037) and far future (2038 – 2052). However, the study found that climate variations hold no significant impact on industrial electricity consumption in Uganda. Drawing upon results from the baseline period and future projections, promoting the efficient utilization of alternative renewable energy sources emerges as a strategic approach to mitigate the burden on hydroelectricity generation and enhance resilience against climate variations in Uganda.

Key words: Climate variability, Electricity markets, Hydropower generation, Renewable energy, Multiple linear regression.

CHAPTER ONE: INTRODUCTION

This chapter introduces the background, statement of the problem, justification, objectives, research questions and the structure of the thesis.

1.1 Background

Climate change and variability stand as critical global concerns, casting their effects across diverse sectors, notably the energy industry. Extensive discussions in the literature have delved into the uncertainties surrounding global precipitation and surface temperature projections (Qasmi & Ribes, 2022; Wu et al., 2022). The scope of potential future climate scenarios carries profound implications for the electricity generation sector, particularly impacting water levels crucial for hydropower generation and the cooling demands of thermoelectric power plants (Van Vliet et al., 2016). When examining the connection between climate change and electricity consumption, it's essential to consider how temperature variations impact this relationship. Below the lower limit of the comfort zone, the relationship between climate change and electricity consumption appears linear. However, once temperatures surpass the upper limit of the comfort zone, this relationship becomes nonlinear (Su & Zhou, 2023). This underscores the significance of temperature fluctuations in influencing electricity usage (Fan et al., 2019; Zhang et al., 2019; Zheng et al., 2020), particularly regarding heating and cooling demands, which are further influenced by factors like heating technology and building insulation (Gallo Cassarino et al., 2018).

Zhang et al. (2019) further highlights that global warming contributes to extreme weather conditions, leading to higher summer temperatures and reduced winter temperatures, consequently driving up electricity consumption in rural China. Similarly, in Australia, there's a heightened sensitivity of electricity demand to temperature fluctuations, especially during summer months (Ahmed et al., 2012). Moreover, climate change could significantly impact electricity generation capacity in the Western United States, potentially leading to reductions in summertime generating capacity (Bartos & Chester, 2015). Projections for future climate change in Greece suggest a substantial impact on electricity demand, with an anticipated increase of 3.6-5.5%, particularly during the summer season, despite moderate declines in the winter (Mirasgedis et al., 2007; Golombek et al., 2012). These studies reveal the importance of considering climate impacts in power providers' development plans to ensure the ability to meet future electricity needs (Bartos & Chester, 2015).

In Africa, a region highly vulnerable to climate-related disturbances, there's a notable gap in understanding the precise impacts of climate change and variability on electricity consumption. The limited exploration of Africa's electricity consumption can be attributed to the scarcity of data on electricity usage (IEA, 2022). Yao, (2021) highlights sub-Saharan Africa as an area with insufficient data availability and heightened vulnerability to climate shocks, given its reliance on nature-dependent income-generating activities. Remarkably, despite the data limitations observed, a few studies have examined the link between climate and electricity consumption in Africa (Momodu, 2017; Ouedraogo, 2017; Diawuo et al., 2020). A study by Karimu & Mensah, (2015) found that temperature variability has a positive permanent effect on electricity consumption in most Sub-Saharan African countries, except for Togo, South Africa, and Zimbabwe, where there is low penetration of air conditioners and heating devices. Bonkaney, (2020) highlighted temperature and GDP per capita as the most influential factors affecting electricity consumption in the four cities of Niger.

In empirical literature, temperature is considered the main climatic variable affecting electricity consumption and highlight the importance of incorporating temperature variations in future energy planning (Gallo Cassarino et al., 2018; van Ruijven et al., 2019; Bonkaney, 2020). However, global and regional research suggests that climate variables have a relatively small impact on electricity consumption, with other variables playing a more significant role (Zhang et al., 2019; Silva et al., 2020). It's essential to recognize that climate varies significantly based on factors such as latitude, proximity to the sea, vegetation, topography, and others (Akhmat et al., 2014). Furthermore, temperature sensitivity varies by a country's latitude, with each country exhibiting its activity profile (Gallo Cassarino et al., 2018).

Uganda features a tropical and humid climate with monthly average maximum temperatures ranging between 24°C - 30°C and annual rainfall exceeding 1500 mm (Kitio et al., 2016). According to the IPCC's special report in 2022, global warming has raised temperatures worldwide at a rate of 1.7°F per century, with projections of an increase by 1.5 degrees Celsius (2.7° degrees Fahrenheit) by 2050 and 2-4 degrees Celsius (3.6-7.2 degrees Fahrenheit) by 2100. In Uganda, daily maximum and minimum temperatures are expected to rise in both the near and far future (Mbogga, 2013; Nsubuga et al., 2014; Nsubuga & Rautenbach, 2018). These temperature increases align with future projections from general circulation models under different scenarios (Ayugi et al., 2021). Research has shown that different sectors, such as residential, commercial, and industrial, respond differently to electricity demand, with residential and commercial sectors displaying greater sensitivity to climate variables (Sridharan et al., 2019). With Uganda's significant potential and heavy reliance on hydroelectricity, climate variability poses a substantial risk to hydro power systems, escalating the likelihood of outages and disrupting demand dynamics. These power shortages have adverse effects on daily life and disrupt trade, industry, and agriculture (Sekantsi & Okot, 2016). Given the absence of Uganda-specific studies, the current research assessed the observed and future impacts of climate variability on electricity consumption to reflect the situation in Uganda, Uganda. Average temperature was used together with rainfall and relative humidity. Nevertheless, it's crucial to include socio-economic variables as non-climate factors when analyzing electricity consumption responses., thus justifying the inclusion of GDP in the analysis.

1.2 Problem statement

Uganda's energy investments, particularly in hydropower to enhance electricity access and optimize energy and financial resources, are based on the assumption that historical precipitation patterns will persist (Sridharan et al., 2019). This assumption exposes the country to significant risks, as climate unpredictability may lead to stranded infrastructure or lost opportunities due to variations in water availability. The most critical climate variations are increased/reduced precipitation and increasing temperature with implications on urban vulnerabilities (UN-HABITAT, 2009). The increased intensity and frequency of extreme weather events such as heavy rainfall storms and floods affect energy infrastructure power plants, transmission lines and power lines that disrupt electricity supply resulting in power cuts and higher energy prices (Office of Prime Minister, 2019). These shifts in climate will inevitably influence electricity demand, amplifying the risk of power system outages. According to the Intergovernmental Panel on Climate Change (IPCC), Uganda's reliance on hydropower increases its vulnerability to projected climate change, which is anticipated to have repercussions on electricity prices, consequently affecting consumer (IPCC, 2022). Notably, increased per capita consumption, driven by extreme temperature variations, such as heatwaves, places a strain on the grid by spiking cooling-related energy demands (Qudrat-Ullah, 2021). Failing to invest in climate-resilient infrastructure can lead to erratic electricity pricing in affected regions (Sridharan et al., 2019). Furthermore, the majority of studies conducted in Africa to assess the impacts of climate change on hydropower generation, particularly stream flow and runoff patterns. This has resulted in a notable gap in understanding the effects of climate change on electricity consumption. Therefore, this study assessed the current and future impacts of climate variability on electricity consumption. It aims to provide valuable insights into how electricity consumption is influenced by climate variations, offering a foundation for climate-resilient planning and policy decisions.

1.3 Justification of the study

Uganda, like many African countries, is susceptible to climate-related disturbances, including increased temperatures, changing rainfall patterns, and extreme weather events. Uganda's energy investments, particularly in hydropower, rely heavily on historical climate patterns, exposing the country to significant vulnerabilities. As the climate unpredictability may lead to stranded infrastructure or lost opportunities due to variations in water availability. In 2021, the Uganda Bureau of Statistics reported a national electricity access rate of 57%, with 19% and 38% having on-grid and off-grid connections, respectively (UBOS, 2020). However, this progress has not been uniform, as rural areas lag with a mere 10% access rate, compared to the national average of 22.1%.

The majority of this increased electricity access is concentrated in urban areas driven by population growth and rapid industrialization, as well as socio-economic development (UBOS, 2020). The sustainability of Uganda’s economy is under threat from climate variations which affect the availability and reliability of electricity, posing risks to both development and social welfare. The unique climate conditions and socio-economic factors in African countries require specialized research to understand their effects on electricity consumption fully. The study is relevant because it aims to address this issue by assessing the impact of climate variability on electricity consumption in Uganda, a region highly vulnerable to climate-related disturbances.

1.4 Objectives of the study

The main objective of this study is to assess the current and future impacts of climate variation on electricity consumption in Uganda

The specific objectives are to:

Identify the trends in climatic conditions in Uganda

1) Show the relationship between current climate variations and electricity consumption in Uganda
2) Simulate future scenarios of the relationship between varying climate conditions and

electricity consumption

3) Show the implications of additional electricity needs in Uganda under a changing climate.

1.5 Research questions

1) What are the current climatic conditions in Uganda
2) What are the characteristics of the current electricity consumption in Uganda?
3) How does climate variability affect electricity consumption in Uganda?

1.6 Hypothesis

1) Climate variability has an influence on electricity consumption in Uganda.
2) There is no significant impact of climate variability on electricity consumption in Uganda.

1.7 Structure of the thesis

The thesis is divided into five chapters as the following:

Chapter One- Introduction: This chapter contains the background, problem statement, justification of the study, objectives of the study and research questions.

Chapter Two- Literature Review: This chapter has the literature review where studies related to the topic is critically examined for what has been done in this research area and the gaps that this study intends to fill.

Chapter Three- Data and methodology: This chapter describes the data and methods that are employed in this study. It explains the reasons for selecting the methods as well as details about models, data preparation, data collection and analysis, and final reporting.

Chapter Four- Results and Discussion: The results of the study are reported and discussed in this chapter.

Chapter Five- Conclusion and Recommendations: The conclusions drawn from this study are highlighted and recommendations are given.

CHAPTER TWO: LITERATURE REVIEW

This chapter reviews the literature on climate variability in Uganda, energy sources and electricity in Uganda, climate change-energy nexus and previous research on climate change impacts on electricity consumption.

2.1 Climate change and variability in Uganda

Research efforts aimed at identifying climate change and variability, has primarily focused on analyzing temperature and precipitation to explain current climate change trends. This collective investigation has painted a global picture characterized by rising temperatures and altered rainfall patterns, which is closely aligned with observations made in Uganda. The changing climate in Uganda, has lead to increased trends of hot days/nights and warm spells (Nsubuga et al., 2014), and extreme meteorological conditions such as droughts, floods, and landslides (Babyenda et al., 2023). Between 1950 and 2021, the temperature increased at a rate of approximately 0.23°C per decade. Over the last thirty-one years, the rate of temperature rise slightly increased to about 0.25°C per decade. By 2021, the temperature had risen to approximately 0.65°C above the long-term average based on data from 1981 to 2010 (UNMA, 2022).

Warming trends observed in recent decades are projected to continue over the 21st century and over most land regions at a rate higher than the global average (IPCC, 2021). Although, there are different views and opinions in the scientific community regarding the origin of climate change. The IPCC 6th assessment report (AR6) highlighted the role of human-induced climate change in exacerbating numerous weather and climate extremes, with implications for heightened climate change risks across all regions, particularly in Africa (IPCC, 2021). Recent studies have identified changes in rainfall patterns in Uganda, notably a decrease in rainfall during the long rainy season (March to May) and an increase in rainfall with higher intensities during the short rainy season (September to November) (Ogwang et al., 2016; Ongoma et al., 2018; Ngoma et al., 2021). These alterations in rainfall seasons bear significant consequences for a considerable portion of the population reliant on agriculture (Nalwanga et al., 2022), and also impact water availability, leading to fluctuating lake levels, stream flow, potentially affecting hydropower production, among other significant implications (Twinomuhangi et al., 2022a).

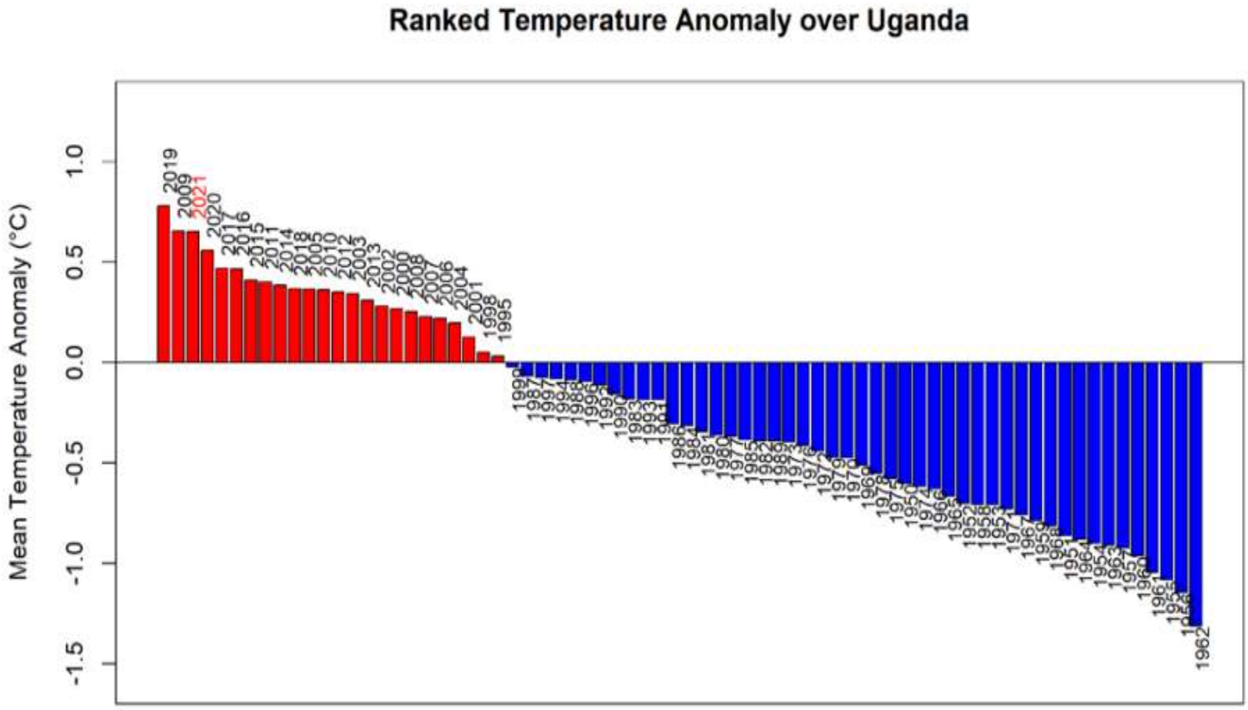


Figure 2.1: Mean annual temperature anomalies (°C) over Uganda for the period 1950 - 2021 relative to 1981-2010. Red color represents years with temperature anomalies more than the long-term mean value (climatology) and blue represents years with temperature anomalies less than the climatology. Source: (UNMA, 2022)

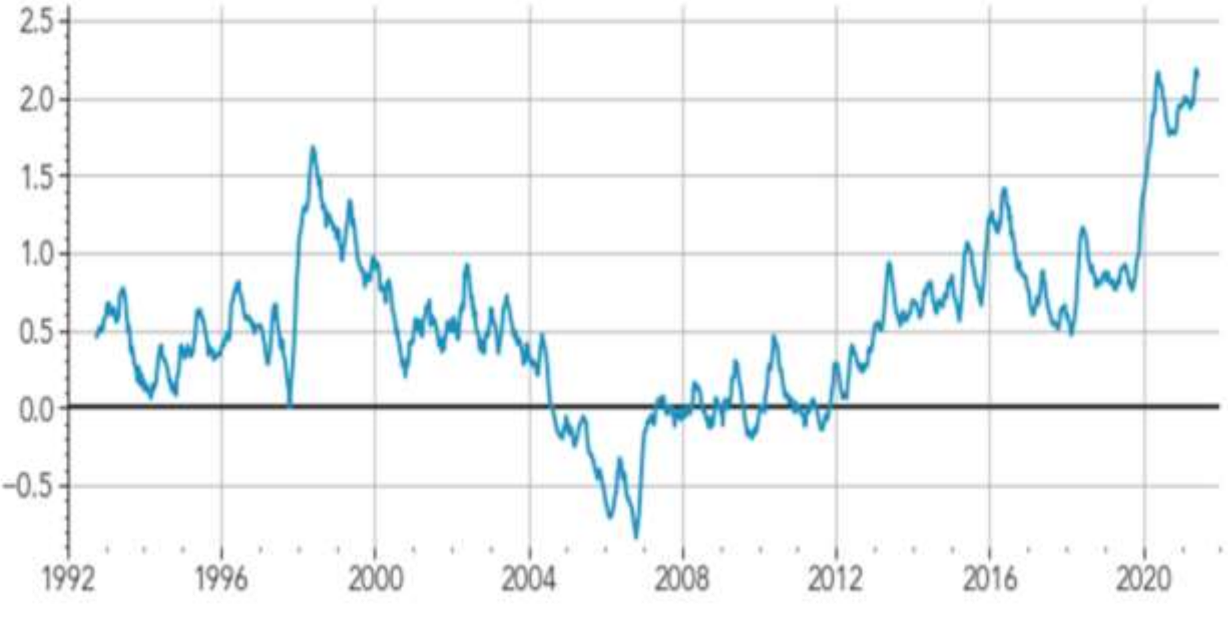


Figure 2.2: The rising waters of Lake Victoria during the rainy season March to June (source: (UNMA, 2022)

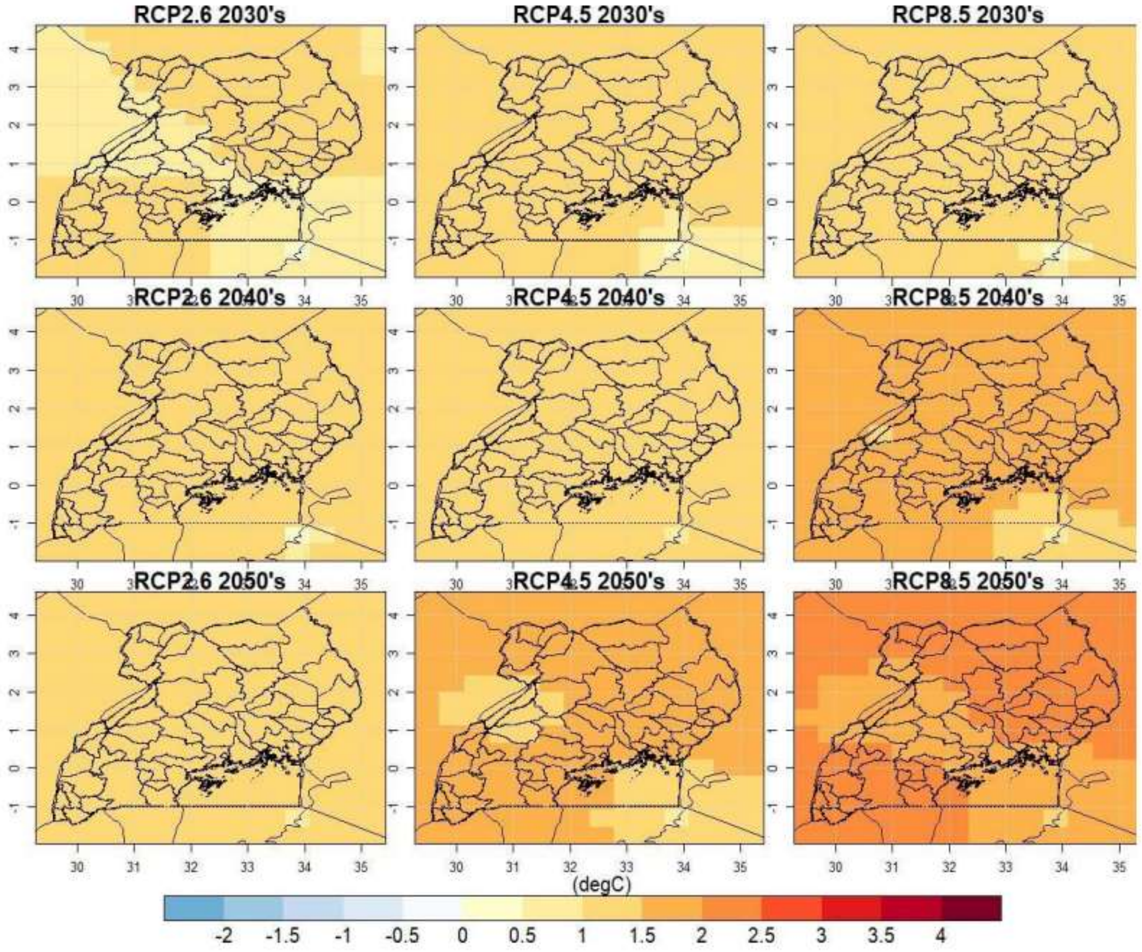


Figure 2.3: Projected mean annual temperature changes per decade from 2030 to 2050s relative to the 1981-2010 average. Source (MWE, 2022)

Recent climate projections based on CMIP6 models show an enhanced decline (increase) in projected rainfall under SSP2-4.5 (SSP5-8.5) over Uganda with a recovery in rainfall towards the end of the century especially in the south-western parts of the country (Ngoma et al., 2022). Under the high green house gas emission scenario (RCP 8.5) for the period 2031-2060, Uganda is projected to experience a rise in mean annual temperatures ranging from 1.5 to 2.5°C compared to the baseline average of 1981-2010 (MWE, 2022). These temperature increases are expected to become evident in the 2040s, and by the 2050s, temperatures across Uganda under RCP 8.5 are projected to range from 1.5 to 3.0°C higher than the 1981-2010 average. Such projections of reduced rainfall across much of Uganda, coupled with notable temperature rises is expected to lead to considerably drier conditions. The extension of the wet season from SON (September to November) towards DJF (December to February) will pose challenges for the country. For instance, a substantial decrease in total rainfall over Lake Victoria (estimated at 20 percent from current levels), along with a projected 1°C temperature increase, will significantly impact the lake's water levels and the livelihoods of communities dependent on activities such as fishing as well as hydropower generation (Nsubuga & Rautenbach, 2018).

2.2 Energy Resources in Uganda

Uganda has abundant energy resources including hydropower, oil and gas, biomass, geothermal, and solar energy. Biomass energy accounts for approximately 88% of the energy mix in Uganda, and only up to 28% of the country's population has access to electricity (Twinomuhangi et al., 2022b). The reliance on biomass energy is a driver of deforestation and forest degradation, which also reduces the country's resilience to climate hazards. Although Uganda possesses substantial potential for hydropower, its current utilization remains minimal, accounting for less than 10% of the total capacity. This underutilization translates to a mere 1% contribution to Uganda's overall energy supply (Adeyemi & Asere, 2014). Solar energy has garnered increasing interest in Uganda, particularly in studies investigating its potential for rural electrification and household applications like lighting, cellphones, and radios (Bongomin & Nziu, 2022). Meanwhile, petroleum remains the dominant energy source for the transportation sector in Uganda, yet its effectiveness is hindered by geopolitical factors and challenges related to importation (Bongomin & Nziu, 2022)

2.3 Electricity in Uganda

The history of Uganda's electricity sector is marked by a series of developments and challenges spanning over a century. Initially recognized for its potential by Sir Winston Churchill in 1905, the sector saw delayed progress due to perceived market limitations (Gore, 2012). However, momentum began in 1936 when discussions between the East African Power and Lighting Company (EAP&L) and Governor Philip Mitchell laid the groundwork for electricity generation and distribution, with commercial services launching in 1938 (Mwaura, 2012). Post-World War II, Uganda's economic focus shifted towards industrialization, with the electricity sector playing a pivotal role in the country's development plans (Gore, 2012). The establishment of the Uganda Electricity Board (UEB) in 1948 aimed at creating a vertically integrated monopoly to supply electricity regionally (Mawejje, 2016). The strategic focus on harnessing the Nile river's potential led to projects like the Owen Falls Dam (Bujagali), operational since 1954, although with challenges such as financial constraints hindering expected socio-economic benefits (Gore, 2012). Plans for the Bujagali project were delayed by political unrest between 1971 and 1986 (Mawejje, 2016).

The electricity sector faced a downturn post-independence, with infrastructure deterioration and a significant drop in capacity (Engurait, 2005). Despite initial resistance, the decision to privatize UEB was reversed in 1999, leading to its unbundling into separate segments for generation, transmission, and distribution. These reforms opened up opportunities for private sector participation in generation and distribution, while the transmission segment remained under government control (Tangri & Mwenda, 2001). The evolution of Uganda's electricity sector reflects a blend of historical initiatives, political dynamics, and economic imperatives, shaping its trajectory towards modernization and efficiency beyond 2005. In spite of apparent governmental dedication to enacting reforms within the electricity sector and undertaking dam construction, Ugandan citizens endured prolonged periods of elevated power costs and frequent instances of load-shedding well into the 2000s (Kjær, 2018). Nevertheless, reforms in the electricity sector, including unbundling, privatization, and the introduction of independent power producers, have led to improved performance and efficiency (Namakula & Faustino, 2023).

Load shedding, which was a major issue in the past, has been greatly reduced due to increased generation capacity and operational improvements in distribution (Byansansa, 2017). Even though the cost of acquiring electricity connections remains high, hindering access for many households, efforts have been made to address these challenges, such as the Rural Electrification Agency's initiatives to increase connections in rural areas (Sebyala, 2020). The daytime electricity demand stands at 260 MW, surging to 350 MW in the evening. This evening peak primarily arises from domestic consumers, who comprise the majority of customers (Umeme, 2019).

2.4 Climate change and Energy nexus

Climate change and energy are closely interconnected. Analyses conducted by the Intergovernmental Panel on Climate Change (IPCC) and various research endeavors highlight the dual relationship between the energy sector and climate change (Akhmat et al., 2014; Sekantsiand & Motlokoa, 2015; IPCC, 2021; Guevara et al., 2023). Not only does the energy sector significantly contribute to climate change through emissions and resource depletion, but it also faces considerable vulnerability to the impacts of climate change itself. The energy sector encompasses a wide array of activities, from fossil fuel extraction and electricity generation to transportation and industrial processes. Energy's contribution to climate change is evident through the burning of fossil fuels being the primary cause. Fossil fuel consumption accounts for more than 75% of global greenhouse gas emissions, including approximately 90% of carbon dioxide emissions (Das & Sharma, 2023). The energy produced from human activities, such as industrialization and urbanization, releases greenhouse gases into the atmosphere. These gases, including carbon dioxide (CO2), trap heat in the Earth's atmosphere, leading to a gradual increase in temperature (Dobruskin, 2023). The increased accumulation of greenhouse gases intensifies the greenhouse effect, where CO2 absorbs and returns infrared radiation, further warming the planet (Planton, 2020). This process has long-lasting effects, potentially persisting for billions of years, significantly impacting the Earth's climate (Dobruskin, 2023).

Furthermore, the energy sector's vulnerability to climate change stems from various factors. Climatic variables, like rainfall and temperature, introduce a high variability in stream flow and the availability of surface water (Atashi et al., 2023). Climate variability significantly influences the generation of renewable energy, with its effects varying based on the energy source (wind, hydropower or solar) (Perera et al., 2020). For instance, shifts in wind patterns can directly affect the efficiency of wind turbines, alterations in water availability have a pronounced impact on hydropower generation, and fluctuations in sunlight intensity directly affect the efficiency of solar panels. Moreover, the geographical location of an area plays a crucial role in determining how climate variability will affect the generation of renewable energy, as highlighted in the research by Wang et al. (2014). Being classified as a Least Developed Country (LDC), Uganda exhibits notably low levels of energy consumption, particularly in terms of fossil fuel usage since the primary source of electricity generation in Uganda revolves around hydro-power, a renewable energy form (Twinomuhangi et al., 2022b). Moreover, Uganda's minimal contribution to global green house gas emissions doesn't diminish its vulnerability to climate change impacts. Despite low emissions, the country faces various climate-related challenges on the energy sector.

In Uganda, climate change poses a significant threat to the country's hydroelectric power production, which plays a crucial role in its energy supply (Ndayishimiye et al., 2022). Extreme climate events such as drought and floods are highlighted to pose immediate risks to hydro power systems, thus disrupting power supply leading to widespread outages (WBG, 2021). In 2020, UMEME Limited (an electricity utility company in Uganda), reported that its operations were adversely affected by climate change impacts, such as thunderstorms, floods, and erratic seasonal variations, leading to substantial losses. The losses were incurred through the need for infrastructure replacement, accidents, and persistent power outages (UMEME Limited, 2020). In the past, droughts in Uganda mainly affected food production causing a decrease in agricultural output, resulting in food shortages for the population. However, in more recent times, specifically during the periods of 2004-2005 and 2010-2011, the droughts had a much more significant impact on flow of the River Nile, which is a crucial water source for Uganda (MWE, 2015). As a result, Uganda faced shortages in electricity supply leading to prolonged daily power outages. Under extreme dry conditions, the amount of power generated by hydropower plants in Uganda could decrease by 91% over the next 40 years. This means that the amount of electricity available for each person in Uganda would be only 19 kilowatt-hours (kWh) per year (Mujjuni et al., 2023). This level of electricity consumption is barely enough to support a decent socioeconomic livelihood.

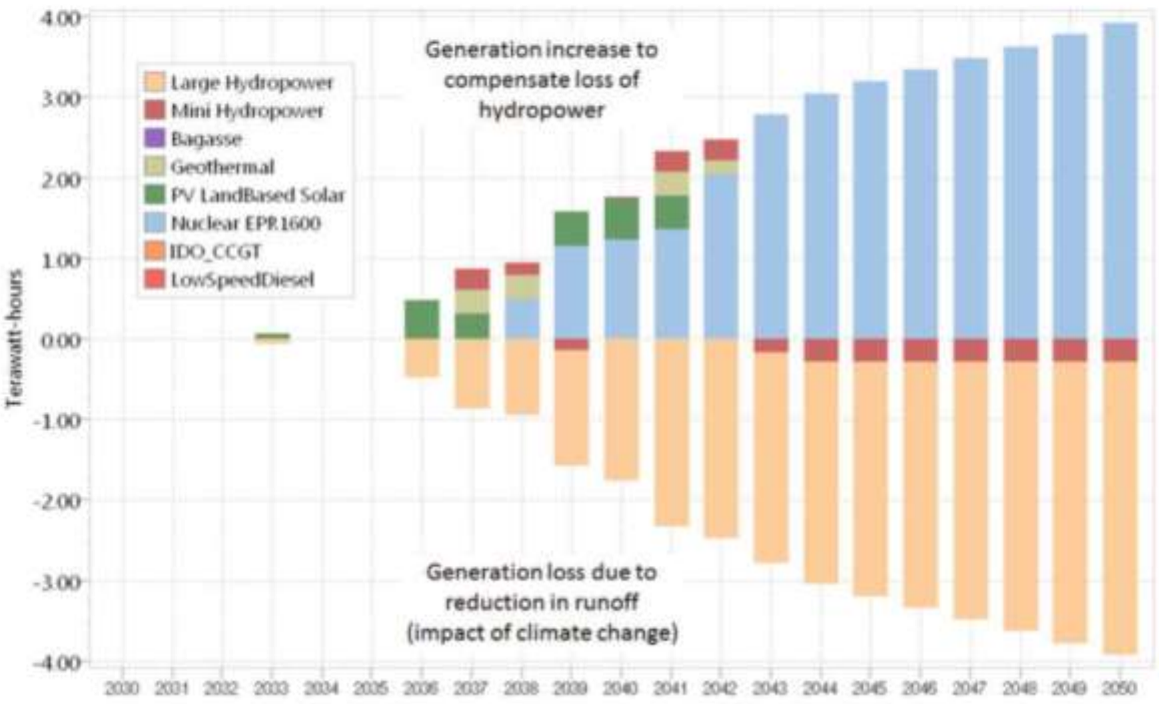


Figure 2.4: Illustration of the impact of climate change on hydropower generation in the scenario of reduced runoff. Source (Twinomuhangi et al., 2022b)

Furthermore, the competition for water resources stemming from climate-induced water stress presents a common challenge among various users. In particular, hydropower infrastructure faces this issue, as water allocation is often prioritized for domestic and agricultural sectors (Yalew et al., 2020). These disruptions caused by climate-induced factors are anticipated to escalate the costs associated with maintaining and repairing power and energy infrastructure, while also disrupting power supply (UMEME Limited, 2020) thereby impacting electricity tariffs. Delving into and understanding electricity's susceptibility to climate change is expected to facilitate the development of predictive models for demand forecasting to help in operational management of electricity systems. (WBG, 2021).

2.5 Climate variability and electricity consumption

Climate variability, notably fluctuations in temperature, has been documented to exert significant impacts across diverse geographical regions. Ahmed et al. (2012) reports that the relationship between temperature and electricity consumption has a U-shaped curve, implying that there exists a critical equilibrium temperature at which heating and cooling demands are in balance. Global electricity demand, both at its peak and overall, is expected to rise in the future due to increasing temperatures. This is because people will likely use more energy for cooling spaces to adapt to hotter weather, which is becoming more frequent and intense (Randazzo et al., 2020). Emodi et al. (2019) found evidence of consistent increase in energy demand for Africa, the Americas and Asian continent. Consistent decrease was found in Northern and Eastern Europe, while increase in residential demand was projected in Oceania. Similarly, research in the Yendi Municipality of Ghana conducted by Iddrisu et al. (2020) highlights that, apart from Relative Humidity, the final energy consumption is influenced by Rainfall, maximum temperature, Sunshine, and Wind. Additionally, according to impulse response analysis, Temperature and Sunshine exert their greatest positive impact on electricity energy consumption in March and September, respectively in Ghana (Iddrisu et al., 2020). In Niger, the sensitivity of electricity consumption is reflected in the monthly seasonal variation index, which reveals consumption peaks in April-May and October, aligning with the hotter months, while consumption dips during December-February, coinciding with the winter period characterized by reduced solar radiation (Bonkaney, 2020).

The sensitivity of electricity consumption to temperature and humidity is lower in West and Central African countries compared to developed countries, but when normalized by base consumption, it is similar (Kondi-Akara et al., 2023). Findings from both global and regional studies indicate that alterations in climate factors, particularly temperature, have a modest influence on electricity consumption. However, it's noted that various other factors play a more significant role in driving electricity usage, as highlighted by Zhang et al. (2019) and Silva et al. (2020). Sub-Saharan African countries, already grappling with substantial electricity shortfalls, face heightened vulnerability to climate change. Research suggests that a mere 1°C temperature rise could escalate electricity demand in these countries by an average of 6.7% (Yao, 2021). Nevertheless, despite experiencing significant temperature increases, particularly within the tropics, including sub-Saharan Africa, these shifts don't induce as significant alterations in electricity demand as slightly larger temperature variations do in mid-latitudes (Romitti & Sue Wing, 2022). However, these findings are constrained by the limited temporal and spatial data available on energy demand in developing countries. Furthermore, temperature sensitivity differentiates electricity use by country's latitude, with each country having its activity profile. Therefore there is need to conduct country-specific investigations on the sensitivity of electricity demand to climate variations (Gallo Cassarino et al., 2018). Hence, further investigation is imperative to understand how climate change impacts electricity systems (Zamanipour et al., 2023), particularly in East Africa, where research in this area remains scarce.

CHAPTER THREE: MATERIAL AND METHODS

In this chapter, a description of the study area is given, additionally, the material and methods used are presented and discussed in their respective sections.

3.1 Study area

Uganda is a landlocked country in East Africa across the equator, located between longitudes 29° 34′ and 35° 0′ East, and latitudes 4° 12′ North and 1° 29′ South. It covers an area of 241,550 km^2 of which 41,743 km^2 (17.2%) is open water and swamps, and the land area is 199,807 km^2. The terrain is mostly plateau raging between 1000 and 2, 500 meters above sea level averaging about 1,200 meters. The lowest point is 620 meters (in the Albert Nile) and the highest point is at 5100 meters (the peak of Mt. Rwenzori) [4]. The main mountain areas are Mt. Rwenzori, permanently snow-capped mountain located in Western Uganda marking the border with the Democratic Republic of Congo (DRC); Mt. Elgon, an extinct volcano in the eastern part of the country at the border with Kenya, and Mt. Muhavura in the south-west bordering Rwanda and D.R.C.

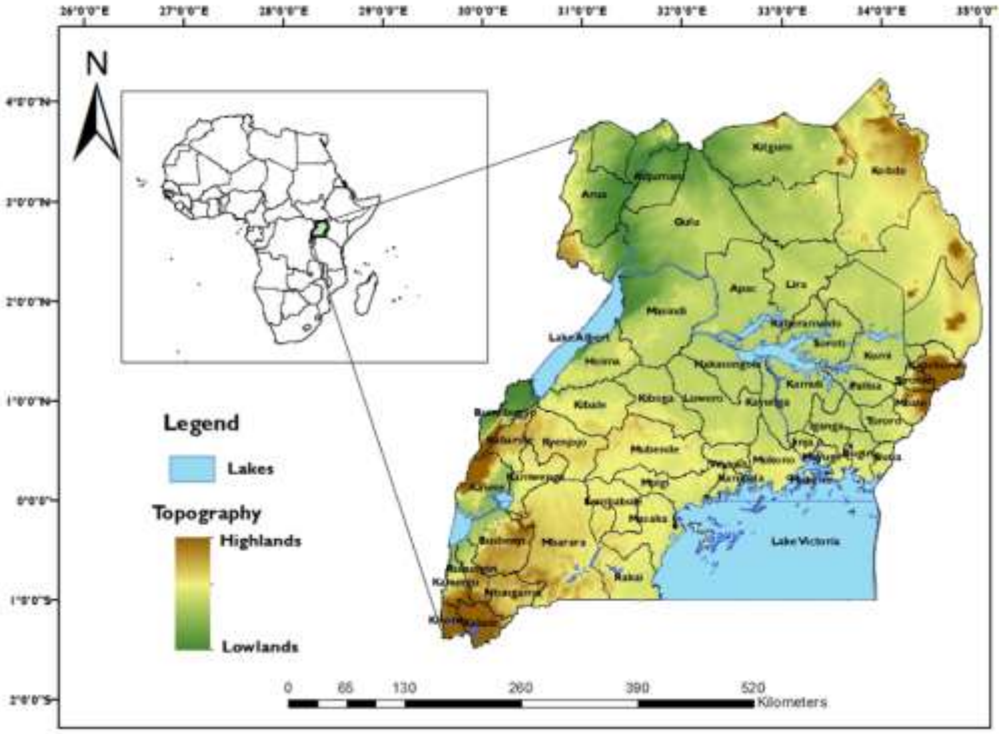


Figure 3.1: Map of showing the location Uganda

Uganda has a pleasant tropical climate, with moderate temperatures and the rainfall is more regular with a bimodal rainfall distribution.

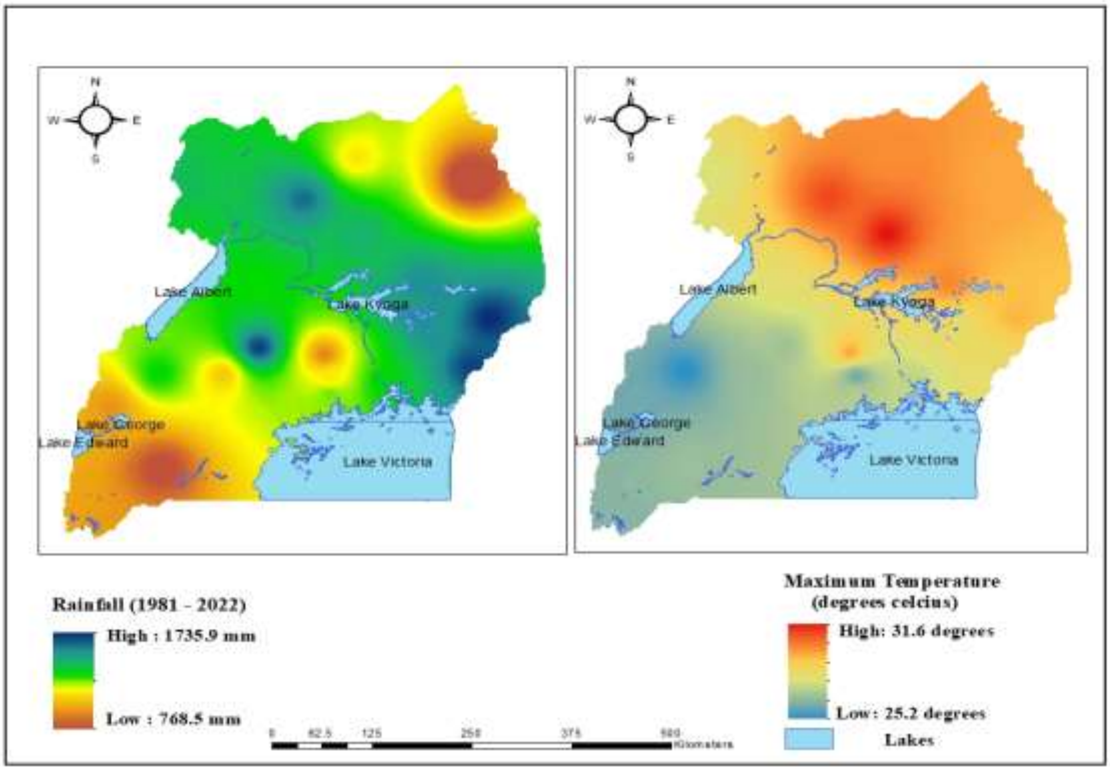


Figure 3.2: Observed spatial distribution of average annual precipitation and temperature

Annual rainfall totals observed in Uganda range from approximately 700 mm to 1800 mm for the period 1981 to 2022. Seasonal rainfall totals in Uganda are characterized by a bimodal cycle (two rainy seasons) in the south, with higher rainfall during the rainy seasons MAM (March-April-May) and SON (September-October-November) (Majaliwa et al., 2015). In the north, a unimodal cycle (one rainy season) becomes more apparent with a longer single rainy season JJA (June-July-August), (Ogwang et al., 2016; Nsubuga, 2018), while the DJF (December-January-February) is a dry season. Throughout the year, the far north-east of Uganda receives little rain. Observed averages in annual near-surface temperatures for Uganda are around 21°C. The highest temperatures are observed in the north, especially in the north-east, while lower temperatures occur in the south (Nsubuga & Rautenbach, 2018). The JJA season is the coolest, while DJF and MAM are the warmest for the Northern region. However, the climate is becoming more variable and changing i.e. temperatures are rising, rainfall is becoming more erratic and unreliable, and extreme weather events are on the rise (Nicholson, 2017). It is widely expected that the impacts of climate change will be felt in varying degrees across all the country's sectors and regions.

3.2 Energy in Uganda

Uganda is a rich country in terms of energy resources which include hydropower, biomass, solar, geothermal, wind, oil and gas. Uganda currently has 850 Megawatts (MW) of installed capacity (with effective generation of approximately 710 MW), of which approximately 645 MW is hydro and 101.5 MW is thermal generating capacity (USAID, 2016). The country has an estimated overall electrical power potential of over 5,300 MW; comprising of 2,200MW of hydropower. However, the country's energy potential has not been fully harnessed. To ensure a sustainable electricity supply, the country has created a conducive regulatory environment and incentives aimed at diversifying the country's energy generation mix. The total installed generation capacity has grown from 60 MW in 1954 to 1,267.2 MW as of 2020 (MEMD, 2020). The Government is investing in the construction of additional large hydropower facilities, such as the 600 MW Karuma hydro plant and the 183 MW Isimba Falls hydro project. There is approximately 1,500 kilometers of transmission lines (over 33kV), which the government aims to double. Additional plans exist to upgrade existing transmission lines and develop an electrification 'ring' around Lake Victoria, in conjunction with Kenya and Tanzania (WBG, 2021).

The Uganda Bureau of Statistics household survey, 2020 found that the national electricity access rate increased to 57% in urban areas, with 19% and 38% having on-grid and off-grid connections (UBOS, 2020). However, access rates drop to 10% in rural areas, compared with just 22.1% nationally (ITA, 2023). In the same year, the Electricity Regulatory Authority (ERA) estimated that Uganda would have an installed capacity of 1,346 megawatts (MW) by December 2021, with demand of 800 MW and a surplus of 546 MW. This increase in access to electricity is largely due to population growth, industrialization and socio-economic development in urban areas, especially in Kampala City and other provincial cities. With a mandate to increase access to electricity and develop a strategy for the best use of the country's energy and financial resources (National Planning Authority, 2020), Majority of these investments in hydropower plants are made on the assumption that precipitation patterns will follow historical trends. Therein lies a significant risk. Any change in water availability could leave this infrastructure stranded or result in lost opportunity costs as a result of failing to capitalize on higher water availability. Uganda's power tariffs are set on a quarterly basis, and the average tariff to consumers is $0.19/kWh ($0.09/kWh for large industrial users), with the first 15 units of power subsidized (ITA, 2023).

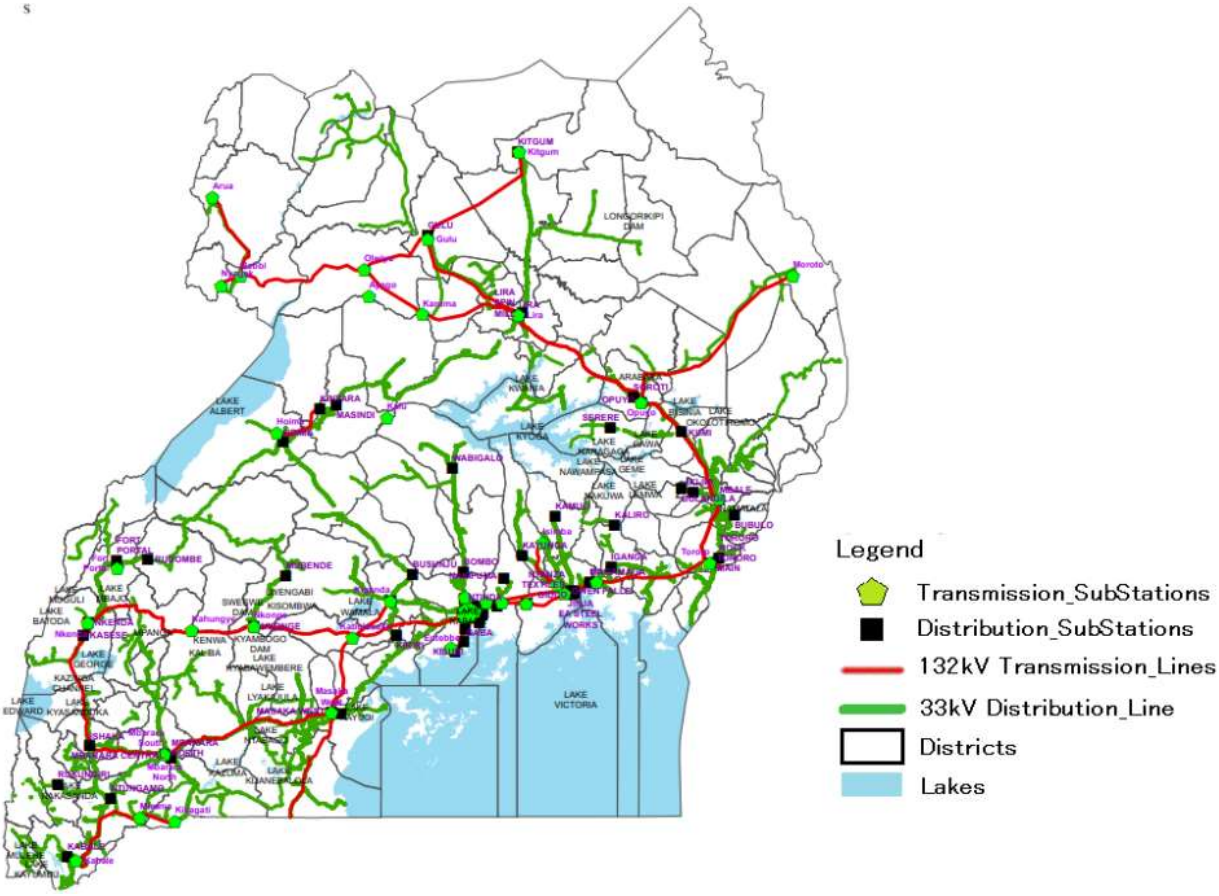


Figure 3.3: Uganda Electricity grid and Sub-stations. source: (Miito & Banadda, 2017).

3.3 Data acquisition

3.3.1 Observed data

Rainfall, relative humidity and average temperature were selected as climate variables. Mean daily climate data for Uganda from 2008 to 2022 was acquired from the Uganda National Meteorological Authority (UNMA), a credible source for all climate data in Uganda. UNMA allows end users to access all climate data for specific date ranges any location in Uganda. Quarterly electricity consumption data from 2008 to 2022 was acquired in the form of electricity sales in billion Uganda shillings from the Electricity Regulatory Authority (ERA). The ERA is a statutory body established in the year 2000, in accordance with the Electricity Act, 1999, (Chapter 145 of the Laws of Uganda) to regulate the Generation, Transmission, Distribution, Sale, Export and Import of Electrical Energy in Uganda. ERA is mandated to establish a tariff structure, approve rates of charges among other functions as well as ensuring a sustainable Electricity Supply (ERA, 2019). Uganda’s power tariffs are set on a quarterly basis, and the average tariff to consumers is \$0.19/kWh (\$0.09/kWh for large industrial users), with the first 15 units of power subsidized. Quarterly gross domestic product (GDP) at market prices from 2008 to 2022 was obtained from the Uganda Bureau of Statistics (UBOS). UBOS is a credible source in Uganda responsible for all statistics in Uganda, from demographic, socioeconomic, production, environment among others. UBOS GDP data was evaluated against the World Development Indicators (WDI) and the results showed that the UBOS series is smoother and produces a more stable measure of GDP than does the WDI series, making the former most appropriate for use when analyzing macroeconomic relationships of Uganda (Bwire, 2014)

3.3.2 Climate projection data

The future climate data employed in this study was obtained from the CORDEX project which was downloaded from the Earth System Grid Federation server https://esgf-data.dkrz.de/search/cordex-dkrz/ The CORDEX is a project funded to provide assessment of model performance, climate change impact assessments and adaptation researches as well as high-resolution of historical and future climate data on a shared platform which will be easily accessible. The CORDEX – Africa datasets are available in daily, 10-day and monthly periods at a spatial resolution of 0.44° × 0.44° which is approximately 50 km × 50 km for the period of 1951 – 2005 (historical) and 2006 – 2099 (future). However, due to the scope of this study, only three GCM under RCA4 were selected and the multi-model ensemble mean was generated. The MME of the three RCMs was employed to delineate the future trends and variability of climatic features over the study domain. The models were as follows: Model for Interdisciplinary Research on Climate (MIROC5), Institute Pierre Simon Laplace Model CM5AMR (IPSL-CM5A-LR) and Max Planck Institute Earth System Model at base resolution (MPI-ESM-LR). The listed RCMs simulations outputs were derived from the dynamical downscaling of CMIP6 GCMs using Rossby Centre regional Atmospheric model (RCA4), originally developed by the Swedish Meteorological and Hydrological Institute (SMHI) under the CORDEX initiative (Samuelsson et al., 2011). The RCA4 is a product of major enhancement on RCA3 based on model experimental design.

Historical daily minimum and maximum temperatures for Uganda simulated by the three RCMs for 1981 to 2005 (30 years) were evaluated against the observed data. Projections of future temperature trends and variability were assessed under low and high emission scenario of Shared Socioeconomic Pathways (SSP 2.6 and SSP 8.5) from 2023–2060 period. The Shared Socioeconomic Pathways (SSPs) encompass a range of potential scenarios, each characterized by unique blends of mitigation and adaptation strategies. SSP 2.6 outlines a trajectory known as the "green road," envisioning a future where societies prioritize sustainability and eco-friendly practices. On the other hand, SSP 8.5 portrays a world heavily reliant on fossil fuels (Rabezanahary Tanteliniaina & Andrianarimanana, 2023).

Average historical/future temperature was obtained by calculating the average of minimum and maximum temperature for Uganda. A summary of all model datasets used is shown in Table 3.1, indicating the type, source and resolution. All datasets were re-gridded using the bilinear interpolation technique to 0.5°×0.5° spatial resolution in the present study. This was aimed to achieve uniform grids for analysis since the gridded datasets were of varying resolutions. Python programing (version 3.6) was utilized to extract the data from Netcdf file format using the coordinates of Uganda. The data were prepared and properly arranged using jupyter notebook and later saved in Microsoft Excel 2016. The MME datasets of three better performing RCMs were recently evaluated by inferring their performance over the study domain (Ayugi et al., 2020). These models were appraised over the broader Greater Horn of Africa (GHA) against observed datasets using various scalar accuracy measures to assess their capability in reproducing fundamental climate data characteristics over the study domain. The statistical metrics included correlation coefficient (CC), mean bias error (MBE), and root mean square difference (RMSD).

Table 3.0.1: The description of the Global Climate Models (GCMs) dynamically downscaled by RCA4 CORDEX

Institute	Native horizontal grid increment	Abbreviated name	References
Institute Pierre-Simon Laplace, France	3.75°× ~1.895°	IPSL-CM5A-LR	Foujols et al. (2012)
National Institute for Environmental Studies, and Japan Agency for Marine Earth Science and Technology (MIROC), Japan	~1.4°×1.4°	MIROC5	Watanabe et al. (2011)
Max Planck Institute for Meteorology (Germany)	~1.875°×1.875°	MPI-ESM-LR	Raddatz et al. (2007)

3.4 Methods

3.4.1 Data processing and Quality control

The daily observed climate data, quarterly electricity consumption data and quarterly GDP from 2008 to 2022 was obtained in soft copy, csv format thus errors in typing were not made. Additionally, climate data from RC4 models was obtained in Netcdf files minimizing errors. In order to achieve the goal and the objectives of this study, several methodologies were applied, including data preparation, data processing and analysis. Data preparation and processing involved organizing of data into formats that can be used for further analysis, checking for missing values and calculating quarterly data from climate datasets. The future assessment comprised of model evaluation and bias correction.

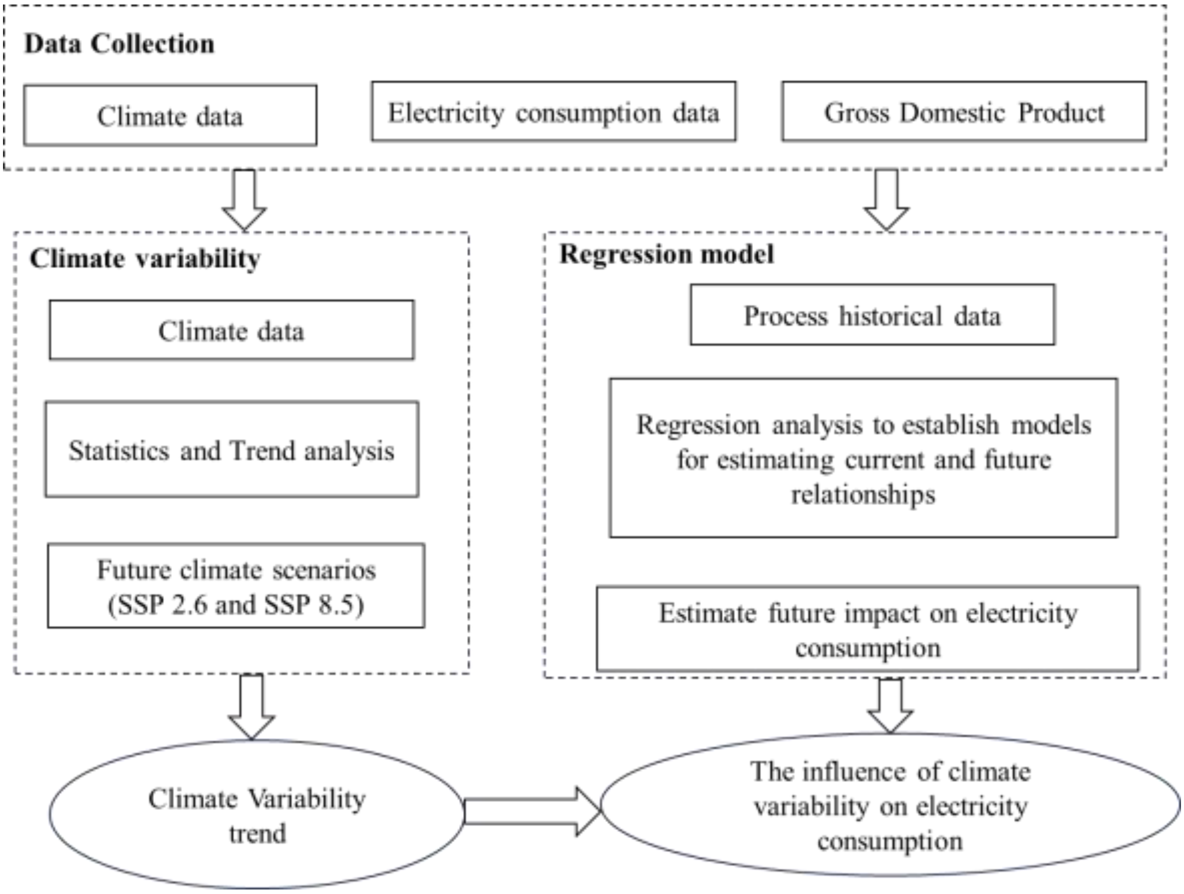


Figure 3.4: The flowchart of the methodology employed in this study

3.4.2 Mann Kendall trend analysis

The Nonparametric (Mann-Kendall tests) statistical procedures were applied on historical data at 5% significant level (Mann, 1945; Kendall, 1975). The benefit of using Mann Kendall trend test were highlighted by Zhang et al. (2011). They include the following: (1) It is a rank-based nonparametric test which can test trends without requiring normality or linearity. (2) This method, like other non-parametric trend detection methods, is less sensitive to outliers. It does not depend on the magnitude of data missing values and space-time of monitoring, (3) This method has been recommended by the World Meteorological Organization. Researchers have adopted this approach to understand the trends in the meteorological parameters (Gocic & Trajkovic, 2013; Nsubuga et al., 2011; Ngoma et al., 2021). The Mann-Kendall trend test is defined as:

$$S = \sum_{k=0}^{n-1} \sum_{j=k+1}^{n-1} sgn\left(X_j - X_k\right) \text{ with } sgn(x) = \begin{cases} 1, & if \quad x < 0 \\ 0, & if \quad x \geq 0 \\ -1, & if \quad x \geq 0 \end{cases} \qquad (1)$$

where X_j and X_k are data values, n is the length of the dataset. Under the null hypothesis, the statistic S is normally distributed when $n \geq 8$ with zero mean and the variance is given as follows;

$$Var(S) = \frac{n(n-1)(2_n+5) - \sum_t^n t(t-1)(2_t+5)}{18} \qquad (2)$$

where t, is the extent of any given tie and denotes the summation over all ties. The Standardized test statistic Z is computed by

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, & for \quad S < 0 \\ 0, & for \quad S \geq 0 \\ \frac{S+1}{\sqrt{Var(S)}}, & for \quad S \geq 0 \end{cases} \qquad (3)$$

3.4.3 Multi Regression Analysis

The multiple linear regression (MLR) models are used to investigate the correlation between the quarterly electricity consumption with the climate variables and the socioeconomic factors. MLR are models with one dependent variable and more than one independent variables.

The general MLR model is given by the equation below;

$$EC = \beta_o + \sum_{i=1}^{n} \beta_n X_n + \varepsilon \tag{4}$$

where EC is the electricity consumption; β_o, β_1, …β_n are the regression constants which are determined by the ordinary least squares method (OLS); X_1, X_2, …X_n are the independent variables; and ε is the error term. From this equation, two different models were generated given by the following. The first model had all the primitive climate variables given by the equation

$$EC = \beta_o + \beta_1 * Temp + \beta_2 * Rf + \beta_3 * RH \tag{5}$$

where Temp, Rf and RH are the independent variables namely, average temperature, rainfall and relative humidity respectively.

In the second model, rainfall and relative humidity were not included, however, GDP was added alongside average temperature to account for the socioeconomic effect as shown in the equation below;

$$EC = \beta_o + \beta_1 * Temp + \beta_2 * GDP \tag{6}$$

The accuracy of the model was verified through the use of mean absolute percentage error (MAPE), and the coefficient of determination R-squared given by equations;

$$MAPE = \frac{100}{n} * \sum_{i=1}^{i=n} \left| \frac{O_i - P_i}{O_i} \right| \tag{7}$$

$$R^2 = \frac{\sum_{i=1}^{n} (P_i - \bar{O}_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O}_i)^2} \tag{8}$$

where P and O are the model simulated and observed values, respectively, i refers to the simulated and observed pairs. These metrics have been used in previous studies (Ahmed et al., 2012; Bonkaney, 2020). The t-value and p-value where then used to test the significance of the independent variables in the MLR model.

3.4.4 Evaluation of the model

The study validated the performance of both RCM datasets against observed dataset by calculating the correlation coefficient CC, root mean squared difference RMSD and standard deviation SD. These metrics have been employed by studies in evaluating model simulation of climate variables (Ayugi et al., 2020; Ngoma et al., 2021). The mathematical formulas of the metrics employed are shown in the following equations:

$$CC = \frac{\sum_{k=1}^{n}(O_i - \bar{O}_i)(M_i - \bar{M}_i}{\sqrt{\sum_{k=1}^{n}(O_i - \bar{O}_i)^2 \sum_{k=1}^{n}(M_i - \bar{M}_i)^2}} \tag{9}$$

$$RMSD = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(M_i - O_i)^2} \tag{10}$$

where M and O are the model simulated and observed values, respectively. i refers to the simulated and observed pairs and N is the total number of such pairs being evaluated.

Taylor’s diagram was used to show the comparison of the aforementioned datasets over the study area. Taylor’s diagram (Taylor, 2001) is based on a graphical representation widely used to provide evaluation and comparison of model performances, with particular emphasis on climate models. It accounts for different statistical features of model outputs and observations, including correlation, variability and centered root mean square error (Izzaddin et al., 2024). All the three metrics were presented on one plot as illustrated mathematically in Equation 11.

$$(E)^2 = \sigma_m^2 + \sigma_o^2 - 2\sigma_m \sigma_{Oo} C \tag{11}$$

where E is centered RMSD, C is correlation coefficient, σ_m and σ_o are standard deviation for the model and observed datasets respectively.

3.4.5 Bias correction

The bias correction technique applied is Quantile Mapping (QM) with linear mapping. The principle of QM technique relies on adjusting the cumulative distribution functions (CDF) of the simulated future RCM data based on observed historical data as given in Equation 12. This method matches the CDF of the simulated future RCM data and the observed historical data together thereby correcting the bias (extremes, intensity and frequency) (Boonwichai et al., 2018). It has been proven that the quality of RCM data and shape of CDF is improved through QM. Quarterly observed and simulated temperature data from 2008 – 2022 (15 years) were used to bias correct the future simulated data (2023 – 2060). QM technique was able to improve the CDFs of the RCM data as shown in figure 4.23. They show that the RCM was overestimating for both scenarios before bias correction.

$$y = F_{hist-1}(F_{RCM}(x)) \tag{12}$$

where y = bias corrected future rainfall values

F_{hist-1} = inverse of the CDF of the observed values

F_{RCM} = CDF of the historical RCM data

x = RCM values to be corrected

QM technique was able to improve the CDFs of the RCM data as shown in Figures 4.23 and 4.24. They show that the RCM was overestimating before bias correction.

CHAPTER FOUR

In this chapter the results which were obtained from the various methods that were used to address the objectives of the present study are presented and discussed in their respective sections. The methods in the study are discussed in chapter three.

4.1 Climate variability and trend analysis

The study investigated climate variability in Uganda by analyzing temperature, rainfall, and relative humidity data spanning from 2008 to 2022. A descriptive statistical analysis was done by calculating the monthly frequency density (Figure 4.1a, 4.1b, 4.1c), mean and standard deviation of each climatic parameter (table 4.1). This was useful in identifying the monthly/annual patterns and fluctuations in these climatic parameters. Table 4.1 shows distinct patterns in temperature, rainfall, and relative humidity across the months of the year in Uganda.

Table 4.0.1: Climatic parameters for Uganda from 2008 to 2022

Month	Average Temperature (^{0}C)		Rainfall (mm/month)		Relative humidity (%)	
	Mean	St.dev	Mean	St.dev	Mean	St.dev
January	24.2	0.9	32.5	11.9	52.5	5.9
February	25.1	0.8	44.4	15.3	53.3	4.8
March	24.9	1.0	106.0	28.1	62.5	5.9
April	23.4	0.8	163.5	22.1	73.1	3.6
May	22.5	0.5	149.9	26.9	74.8	2.3
June	22.2	0.6	88.3	17.4	71.3	3.6
July	22.2	0.6	96.7	18.9	70.3	3.2
August	22.5	0.6	126.1	24.2	72.2	3.3
September	22.7	0.6	130.6	19.3	73.1	2.8
October	22.6	0.5	146.6	22.5	73.9	3.8
November	22.5	0.6	114.2	28.0	71.9	3.9
December	23.1	0.8	56.8	19.0	61.9	5.7

Additionally, a comparative analysis of temporal variations of the climate parameters was presented in Figures 4.1c, 4.2c and 4.3c using standardized anomalies to measure how much a climate variable in a given year differs from what is considered normal. Extremes are categorized as either above or below normal of these anomalies. If the standardized anomaly value was ⩾ +1, it means the climate variable was above normal (higher than the long-term average). Conversely, values ⩽ -1 indicated below the long-term average. Similar criteria were used in previous studies (Jury, 2018; Ongoma et al., 2018; Oo et al., 2023).

4.1.1 Temperature variability

The temperature in Uganda remains relatively stable throughout the year, with minor fluctuations ranging from 22.2°C to 25.1°C (table 4.1). The consistent occurrence of temperatures between 22°C to 25°C (figure 4.1) suggests a relatively stable thermal comfort range in Uganda. In such conditions, there might be less demand for heating or cooling systems compared to extreme temperature conditions. Consequently, with such a thermal comfort, energy demand for heating or air conditioning, may be relatively low in Uganda. This temperature also shows the potential of Uganda in solar power generation for electricity as solar photovoltaic (PV) systems can operate efficiently without experiencing performance issues due to excessive heat. The temporal variation in temperature reveals a decreasing trend (figure 4.1(c)) in average temperature during the period of 2008 to 2022 over Uganda. Certain years, like 2009 and 2010, recorded significant positive deviations from the mean temperature, signifying periods of warmer temperatures. While some years demonstrated relatively small deviations, others, such as 2020, exhibit exceptionally large negative deviations (-2.74 ^{0}C) suggesting a substantial deviation below the normal and potentially indicating periods of anomalously cooler temperatures. These extreme negative deviations, raise the possibility of anomalous temperature events or localized cooling phenomena within Uganda during that year. Some studies highlighted the decrease in temperature during the period of 2019/2020 and attributed it to the lockdown that happened during the COVID-19 pandemic that reduced emissions of greenhouse gases in the atmosphere (Chen et al., 2023; Guevara et al., 2023)

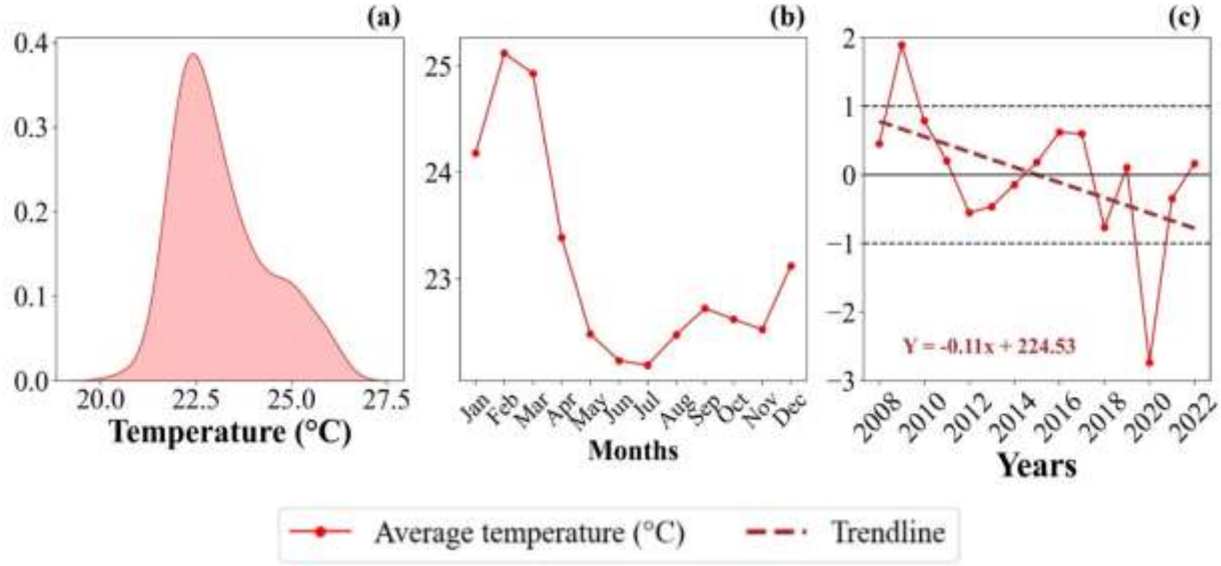


Figure 4.1: Distribution of Temperature over Uganda from 2008 to 2022

4.1.2 Rainfall variability

On average, the mean annual rainfall in Uganda from 2008 to 2022 was approximately 1257.41 mm. The Variability in Rainfall was significant, with peak values observed in April, May, and October, while January recorded the lowest rainfall (table 4.1). This revealed a bimodal rainfall pattern, characterized by two rainy seasons (March to May and September to November) and two dry seasons (December to February and June to August), which is consistent with previous studies on Uganda's climate (Majaliwa et al., 2015; Ogwang et al., 2016; Nsubuga & Rautenbach, 2018). Furthermore, Figure 4.2 (a) shows a high frequency of rainfall amount between 100 to 200mm/month. Rainfall amounts falling within this range can have significant impacts on the environment, particularly in terms of water availability which is crucial for hydro power generation. However, frequent rainfall within the 100 to 200mm/month range highlights the vulnerability of hydropower generation to rainfall variability. Intense or prolonged rainfall events within this range can lead to challenges related to infrastructure resilience such as flooding, erosion which can pose risks to hydropower infrastructure, affecting its operational efficiency, longevity and electricity supply. According to (Mideksa & Kallbekken, 2010), variations in rainfall have the potential to alter river flow, which in turn can alter hydropower generation. The researchers report that greater potential for hydropower generation is indicated by increased rainfall and river flow, but the effect could be adverse if river flow surpasses the capacity of current structures. However, (Mideksa & Kallbekken, 2010) go on to suggest that rainfall extremes, such as storms and heavy rain, might directly harm the end-user since they demolish electricity infrastructure and cause expensive interruptions in the provision of electricity. Meanwhile, the temporal analysis (figure 4.2 (c)) reveals deviations in rainfall among certain years. For instance, the year 2015 exhibited relatively higher rainfall totals above normal compared to other years, whereas 2011 and 2020 recorded lower-than-average rainfall amounts.

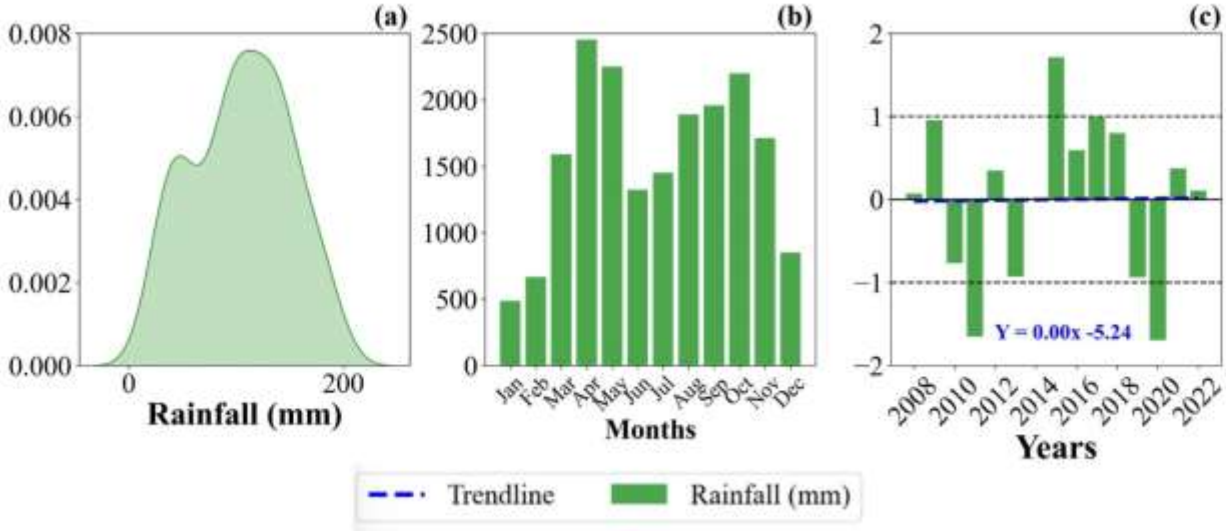


Figure 4.2: Distribution of Rainfall over Uganda from 2008 to 2022

4.1.3 Relative humidity variability

Relative humidity remained relatively stable, ranging from 61.9% to 74.8% across the months (figure 4.3 (b)). The higher humidity levels correlate with the rainy seasons (table 4.1), which is expected due to increased evaporation and moisture in the air. Furthermore, relative humidity had a decreasing trend with below normal anomalies recorded for 2016,2017, 2021 and 2022 while 2010, 2019, 2020 and 2021 were above normal.

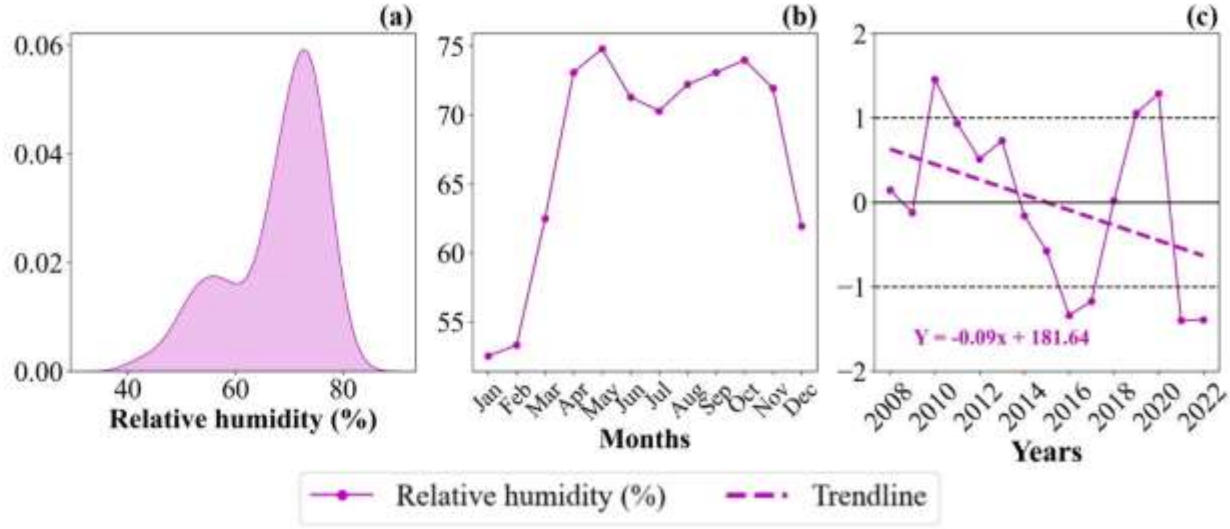


Figure 4.3: Distribution of relative humidity over Uganda from 2008 to 2022

Overall, the variability analysis for the period from 2008 to 2022 shows that the climate in Uganda varies annually and interannually. It highlights the dynamic nature of the Uganda's climate system, characterized by both moderate fluctuations and extreme anomalies. Fluctuations in climate patterns underscore the challenges posed by climate variability and change, impacting various sectors including energy, water resources, and human health. The presence of extreme deviations from the mean emphasizes the vulnerability of Uganda to climatic extremes.

4.2 Current impact of climate variability on electricity consumption

4.2.1 Sectoral electricity consumption

Electricity consumption in Uganda is presented in three sectors, domestic, commercial and industrial electricity consumption from 2008 to 2022. The domestic sector represents household electricity consumption, the commercial sector represents consumption in businesses, offices, and services, and the industrial sector represents the average of electricity consumption from both medium and large-scale industries/factories in Uganda.

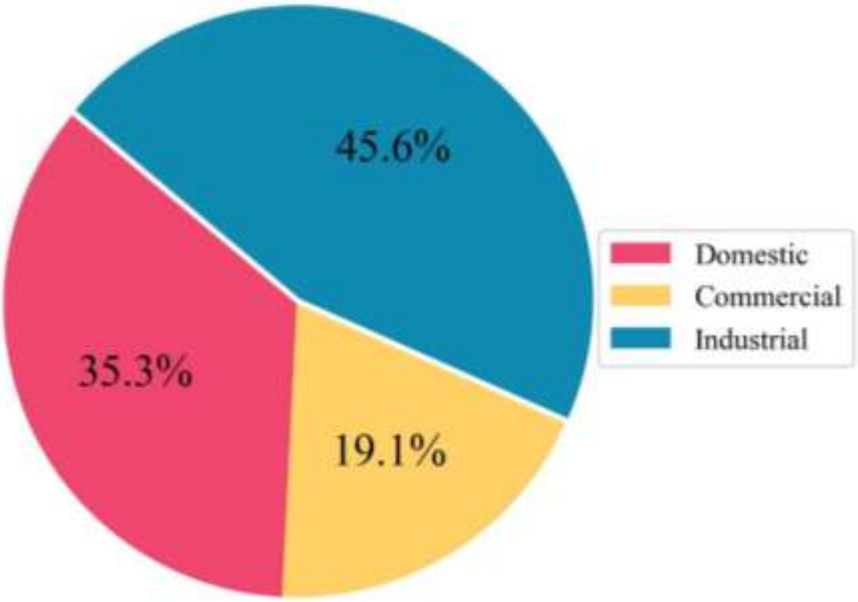


Figure 4.4: Total share of electricity consumption by sector in Uganda from 2008 to 2022

Figure 4.4 shows the total share of the three sectors where the industrial sector, accounts for the largest chunk at 45.6%, followed by the domestic sector at 35.3% and then the commercial sector at 19.1%. This denotes that industries and manufacturing processes are the largest consumers of electricity in Uganda. Notably, a relatively substantial portion of electricity produced in Uganda is directed towards powering homes for activities like lighting, cooking, and refrigeration, highlighting the pivotal role of electricity in facilitating daily domestic routines and enhancing quality of life for individuals and families across Uganda. While the share of commercial electricity consumption is comparatively smaller than the domestic and industrial sectors, the observed proportion still shows a significant amount of electricity being harnessed for commercial pursuits fostering economic growth and development. This suggests the critical role of businesses and service providers in driving economic activities and utilizing electricity for operational needs.

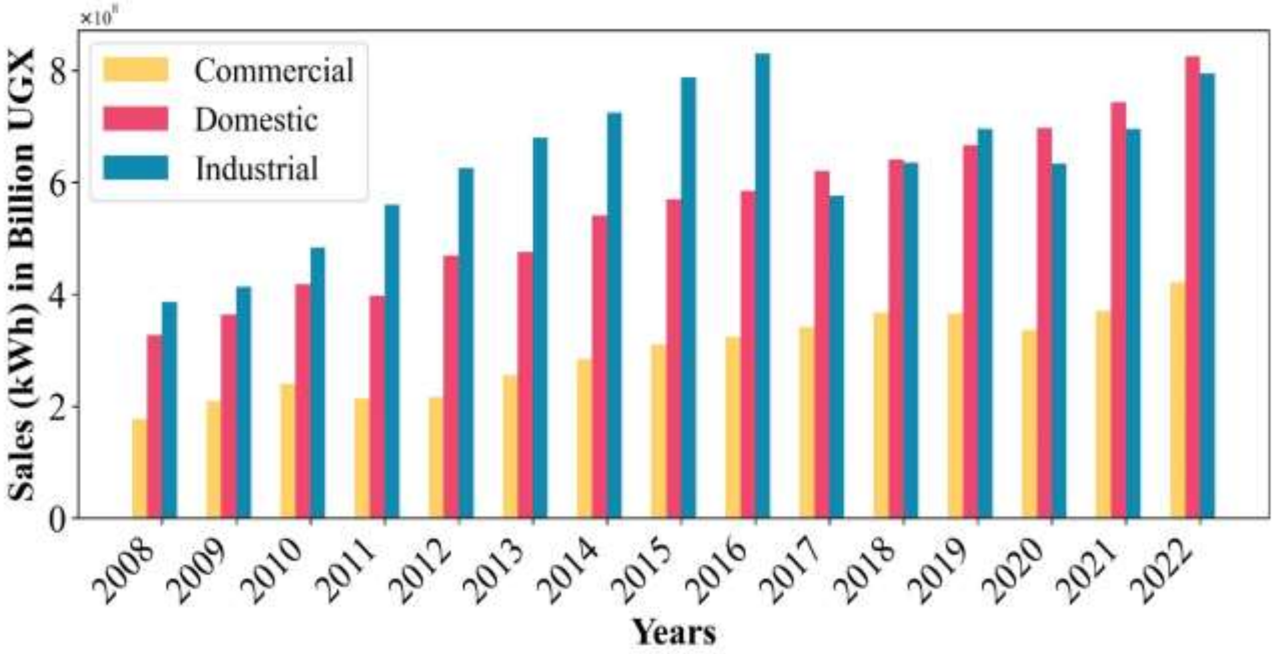


Figure 4.5: Timeseries of electricity consumption in Uganda for domestic, commercial and industrial sectors during the period 2008 to 2022

Domestic electricity consumption (DEC)

The increasing trend of electricity consumption within the domestic sector from 2008 to 2022 displays a fundamental shift in energy utilization patterns among households. Beginning at approximately UGX 327.44 billion (kWh) in 2008 to an estimated UGX 825.58 billion (kWh) by 2022, the trajectory indicates a substantive rise in electricity consumption in Uganda within residential settings. The observed trend signifies a profound improvement in living standards among Ugandan households over the study period. Consequently, the increase in domestic electricity consumption embodies a determined national endeavor towards universal electrification, underpinning broader developmental requirements and aspirations (National Planning Authority, 2020).

Commercial consumption

Just like domestic electricity consumption, the trend of electricity consumption within the commercial sector suggests that businesses and offices in Uganda are using more electricity over time. For instance, in 2008, around UGX 176.73 billion (kWh) was spent on electricity consumption, and by 2022, it went up to about UGX 421.78 billion (kWh). The observed growth hints at a developing economy where businesses are thriving and possibly expanding their operations. This growing trend is statistically significant according to the Mann Kendall results in table 4.2. A rise in commercial electricity consumption usually means there's more economic activity going on, that is, more commercial places are operating and needing electricity to run their operations. This could be because more companies are starting up, existing ones are growing, or there's simply more demand for goods and services. From retail establishments and hospitality ventures to financial institutions and corporate entities, the observed trend attests to the robustness and diversification of Uganda's commercial sector. Also, the increase might suggest that more people are moving to cities or towns, where most businesses are located. As urban areas grow, so does the need for services and facilities, like infrastructural advancements, technological innovations, and demographic shifts, all of which lead to more electricity use within the commercial sector. Overall, the rise in electricity consumption in the commercial sector reflects positive economic developments and trends towards urbanization and electrification in Uganda.

Industrial consumption

Meanwhile, the amount of electricity used by factories and industries in Uganda has changed over time. In 2008, they used about UGX 386.19 billion (kWh). The usage went up and hit its highest point in 2016, reaching about UGX 830.45 billion (kWh). However, it went down a bit after that, settling at around UGX 794.68 billion (kWh) by 2022. These ups and downs suggest that there have been changes in how much electricity industries need. It could be because of shifts in what industries are doing, changes in the economy, or differences in how they use energy. Even though the amount of electricity used has fluctuated, industries in Uganda still use a lot of electricity. This shows that industry and manufacturing are important parts of Uganda's economy. Despite the variations, the industrial sector's significant electricity consumption highlights its role in Uganda's economic landscape. Nevertheless, the Mann Kendall results (table 4.2) revealed that the increasing trend in this sector was not significant during the period of study.

Electricity consumption and Gross Domestic Product

Figure 4.6 indicates that GDP, which measures the value of goods and services produced in an economy, has generally risen over time. However, it's not a smooth ride – there are ups and downs observed in the pattern of GDP over the study period.

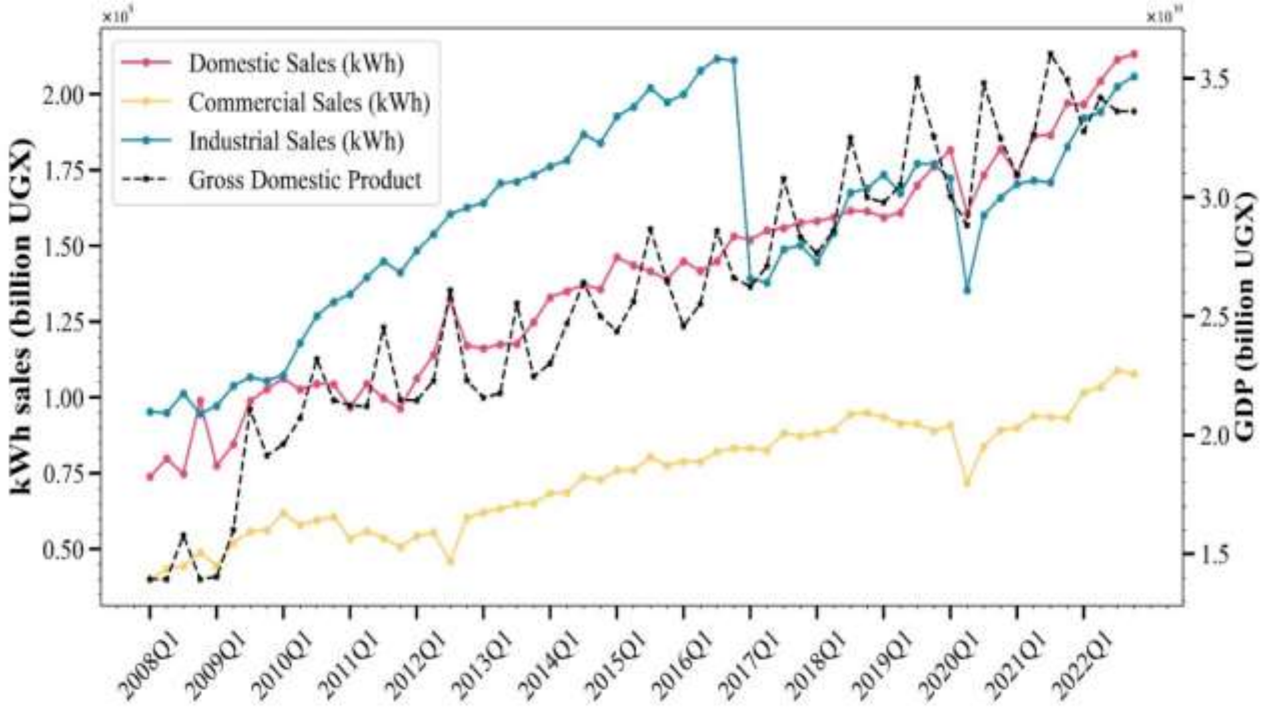


Figure 4.6: Timeseries of quarterly electricity consumption and gross domestic product in Uganda from 2008 to 2022

The significant increasing trend of GDP (table 4.2) is similar to the trend in electricity consumption for the three sectors discussed earlier. This suggests that as the economy grows, there's an increase in the usage of electricity in Uganda. Factors such as population growth, changes in household income, lifestyle preferences, business growth, technological advancements, shifts in consumer behavior, industrial expansion and production demands may contribute to this increasing trend. Nevertheless, the economy takes a hit, like in 2008-2009 and during the COVID-19 pandemic in 2020, both GDP and electricity consumption tend to decline. This is because during 2020, production and processing was low due to the lockdown, businesses and offices were closed, people spent less, and overall demand for electricity decreased as a result (Kizza et al., 2023). In essence, the data paints a picture of a dynamic relationship between economic growth and electricity consumption, with each influencing the other in some way.

Table 4.0.2: Mann Kendall trend results

Trend analysis	**Climate data**			**Electricity sales (kWh)**			**GDP**
	Rainfall	Av. temp	RH	Domestic	Commercial	Industrial	
trend	No trend	Decreasing	No trend	Increasing	Increasing	Increasing	Increasing
P value	0.73	0.01	0.47	0.00	0.00	9.57	0.00
Slope	0.02	-0.00	-0.00	2040559.56	1027125.22	1590130.25	310381915.77
Z	0.34	-2.75	-0.72	10.35	9.37	6.12	9.46
Kendall's tau	0.02	-0.14	-0.04	0.92	0.83	0.54	0.83
Alpha	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Significance	NST	DST	NST	IST	IST	INST	IST

***NST** – No significant trend, **IST** – Increasing significant trend, **DST** – Decreasing significant trend, **INST** – Increasing no significant trend.*

4.3 Impact on electricity consumption

The study investigated the influence of climate variables on electricity consumption in Uganda as well as incorporating the socioeconomic aspect of GDP. The influence of climatic and socioeconomic variables was presented in Multi linear regression models as discussed in equations 5 and 6. Additionally, model evaluation was done using statistical metrics of R-squared and MAPE as discussed in chapter three.

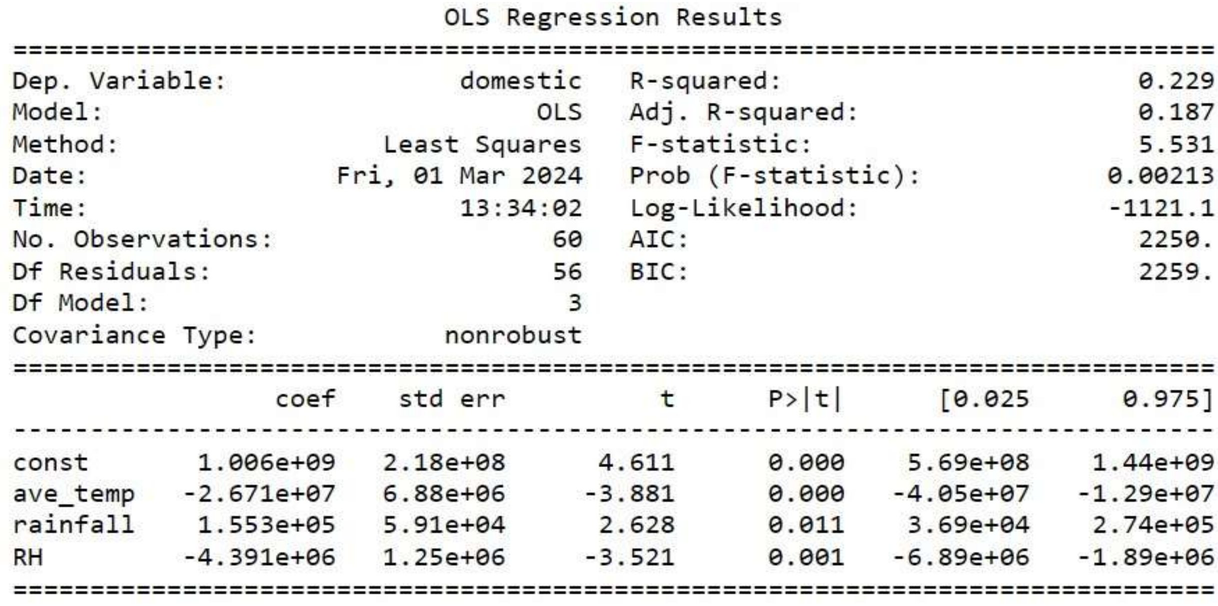
Graphical presentations of the relationship are shown for each sector in figures 4.8, 4.10 and 4.12. The color bar provides insight into the density of data points at different climate and electricity consumption combinations. Red points indicate areas of stronger correlations or more significant trends in the relationship between a variable and electricity consumption. Green/blue points represent moderate/lower correlations. The clustered distribution of points shows that there is a higher likelihood of correlation between a variable and electricity consumption while sparse distribution indicates lower likelihood. When the regression line is horizontal, it indicates no relationship. Meaning that the independent variable does not provide useful information for predicting or explaining the variation in the dependent variable. Whereas, a regression line from left to right and from right to left indicates a positive/negative relationship respectively. Implying that the independent variable provides useful information for predicting or explaining the variation of the dependent variable. A steeper slope (closer to vertical) indicates a stronger relationship, while a shallower slope (closer to horizontal) suggests a weaker relationship.

4.3.1 Average temperature, rainfall and relative humidity

The relationship between electricity consumption and climate, specifically temperature is in a way that electricity consumption increases with low temperature due to heating requirements and also with high temperature due to cooling requirements (Ahmed et al., 2012). It is yet unclear how variations in rainfall and relative humidity might influence electricity consumers. In this first model, the study investigates the impact of primitive climate variables without the aspect of GDP to show the extent and strength of the relationship between the dependent and independent variables.

Domestic electricity consumption (DEC)

The results show that the coefficient for average temperature is -2.671e+07, implying that for every one-unit increase in average temperature, assuming everything else stays the same, domestic electricity consumption tends to decrease by approximately 2.671e+07 units. Looking at rainfall, the coefficient is 1.553e+05, meaning that when rainfall increases by one unit, with other factors constant, domestic electricity consumption tends to go up by about 1.553e+05 units. This might be because people use more electricity during rainy weather, perhaps for heating or lighting. Meanwhile, the coefficient of relative humidity is -4.391e+06, implying that with every one-unit increase in relative humidity, keeping other factors constant, domestic electricity consumption decreases by approximately 4.391e+06 units. This means that as humidity levels rise, people tend to use less electricity. This relationship is graphically represented in figure 4.8. All the coefficients have associated p-values less than 0.05, indicating statistical significance at the 95% confidence level. This shows that all three independent variables (average temperature, rainfall, and relative humidity) are statistically significant in explaining the variation in domestic electricity consumption in Uganda for the study period. The R-squared value is 0.229, suggesting that approximately 22.9% of the variance in DEC is explained by the independent climate variables included in the model.



```
                            OLS Regression Results
==============================================================================
Dep. Variable:               domestic   R-squared:                       0.229
Model:                            OLS   Adj. R-squared:                  0.187
Method:                 Least Squares   F-statistic:                     5.531
Date:                Fri, 01 Mar 2024   Prob (F-statistic):            0.00213
Time:                        13:34:02   Log-Likelihood:                -1121.1
No. Observations:                  60   AIC:                             2250.
Df Residuals:                      56   BIC:                             2259.
Df Model:                           3
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const       1.006e+09   2.18e+08      4.611      0.000    5.69e+08    1.44e+09
ave_temp   -2.671e+07   6.88e+06     -3.881      0.000   -4.05e+07   -1.29e+07
rainfall    1.553e+05   5.91e+04      2.628      0.011    3.69e+04    2.74e+05
RH         -4.391e+06   1.25e+06     -3.521      0.001   -6.89e+06   -1.89e+06
==============================================================================
```

Figure 4.7: Multilinear regression results for the relationship between climate variables and DEC in Uganda from 2008 to 2022

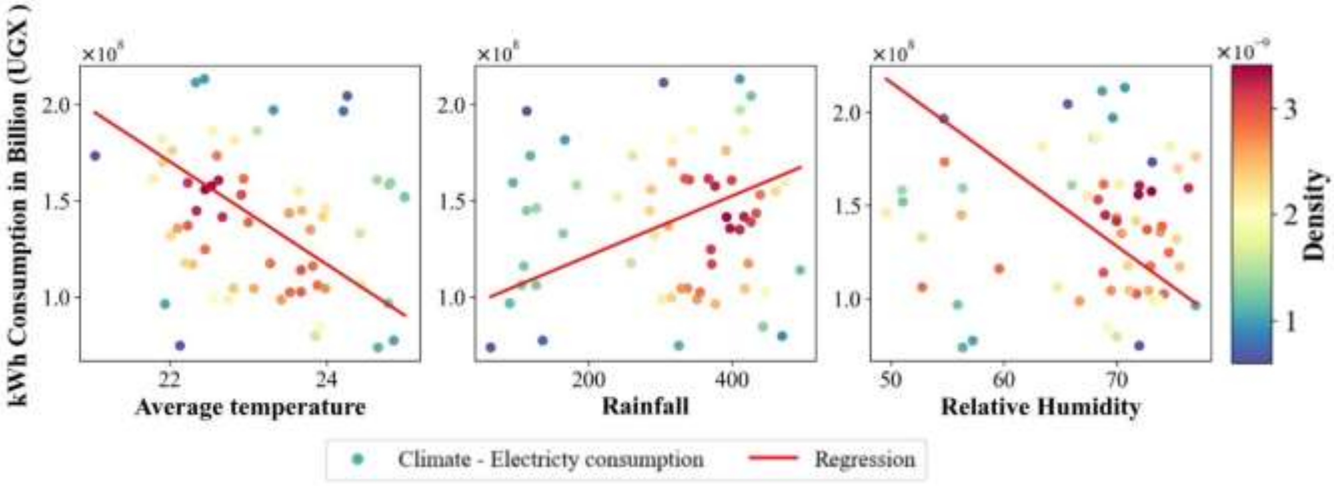
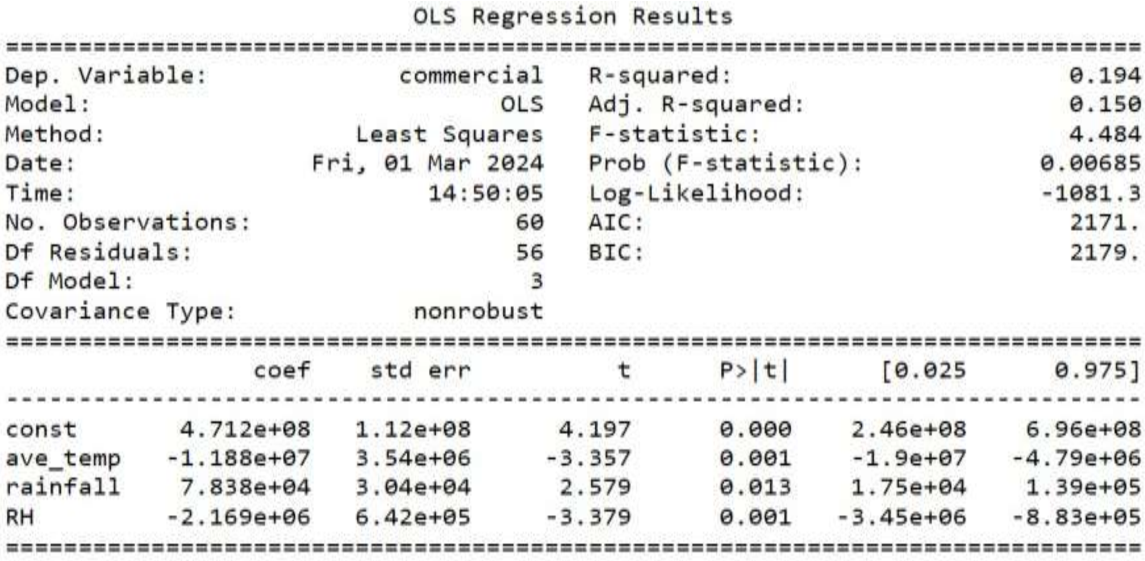


Figure 4.8: Relationship between climate variables and DEC

Commercial electricity consumption (CEC)

Similarly, the coefficient of average temperature is negative and statistically significant at 0.05 significant level. This suggests a response pattern similar to domestic electricity consumption, where the demand for electricity consumption decreases a change in temperature. Meaning that a decrease in temperature results in a negative relationship with electricity consumption. Rainfall and relative humidity also reveal a similar relationship like for DEC where an increase in rainfall/relative humidity may increase/decrease electricity use in commercial establishments respectively. This relationship is statistically significant for all the climate variables used in the model and was graphically represented in figure 4.10. The R-squared value is 0.194, suggesting that approximately 19.4% of the variance in CEC is explained by the independent climate variables included in the model.



```
                            OLS Regression Results
==============================================================================
Dep. Variable:             commercial   R-squared:                       0.194
Model:                            OLS   Adj. R-squared:                  0.150
Method:                 Least Squares   F-statistic:                     4.484
Date:                Fri, 01 Mar 2024   Prob (F-statistic):            0.00685
Time:                        14:50:05   Log-Likelihood:                -1081.3
No. Observations:                  60   AIC:                             2171.
Df Residuals:                      56   BIC:                             2179.
Df Model:                           3
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const       4.712e+08   1.12e+08      4.197      0.000    2.46e+08    6.96e+08
ave_temp   -1.188e+07   3.54e+06     -3.357      0.001    -1.9e+07   -4.79e+06
rainfall    7.838e+04   3.04e+04      2.579      0.013    1.75e+04    1.39e+05
RH         -2.169e+06   6.42e+05     -3.379      0.001   -3.45e+06   -8.83e+05
==============================================================================
```

Figure 4.9: Multilinear regression results for the relationship between climate variables and CEC in Uganda from 2008 to 2022

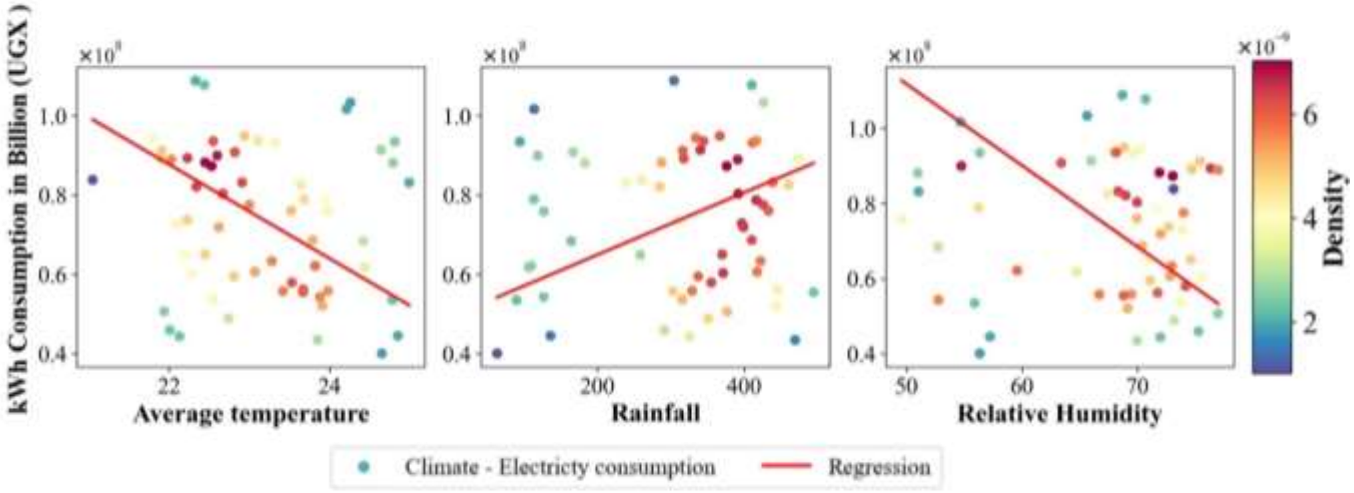
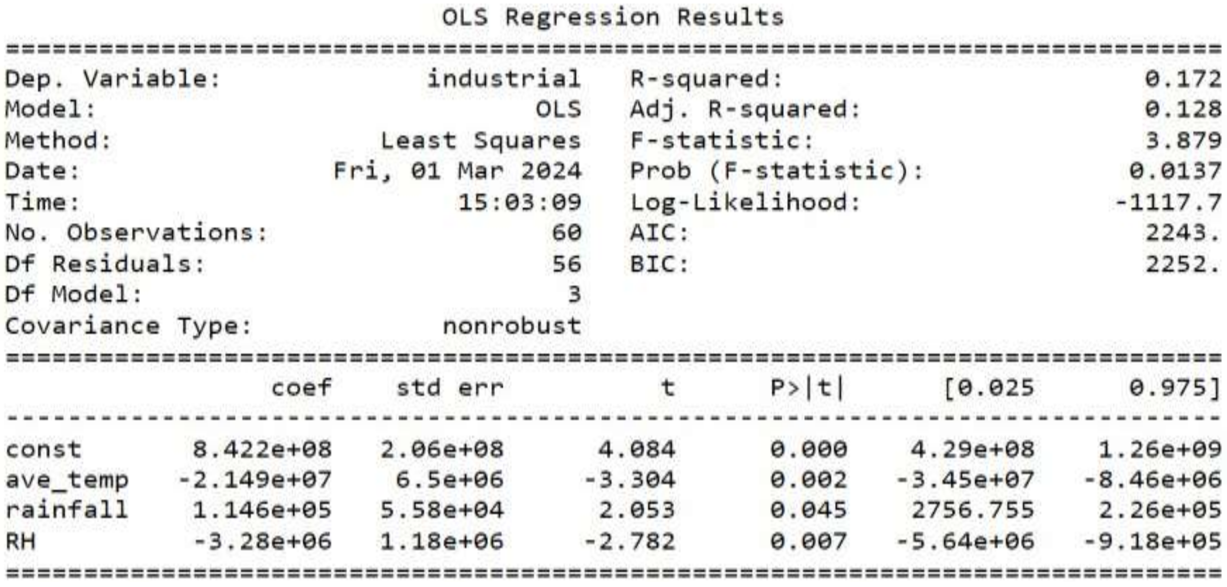


Figure 4.10: Relationship between climate variables and CEC

Industrial electricity consumption (IEC)

The relationship with IEC is not different for that of DEC and CEC for average temperature, rainfall and relative humidity. The R-squared value is 0.172, suggesting that approximately 17.2% of the variance in IEC is explained by the independent climate variables included in the model. Figure 4.12 shows the weak relationship between climate variables and IEC over Uganda.



```
                            OLS Regression Results
==============================================================================
Dep. Variable:             industrial   R-squared:                       0.172
Model:                            OLS   Adj. R-squared:                  0.128
Method:                 Least Squares   F-statistic:                     3.879
Date:                Fri, 01 Mar 2024   Prob (F-statistic):             0.0137
Time:                        15:03:09   Log-Likelihood:                -1117.7
No. Observations:                  60   AIC:                             2243.
Df Residuals:                      56   BIC:                             2252.
Df Model:                           3
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const       8.422e+08   2.06e+08      4.084      0.000    4.29e+08    1.26e+09
ave_temp   -2.149e+07    6.5e+06     -3.304      0.002   -3.45e+07   -8.46e+06
rainfall    1.146e+05   5.58e+04      2.053      0.045    2756.755    2.26e+05
RH          -3.28e+06   1.18e+06     -2.782      0.007   -5.64e+06   -9.18e+05
==============================================================================
```

Figure 4.11: Multilinear regression results for the relationship between climate variables and IEC in Uganda from 2008 to 2022

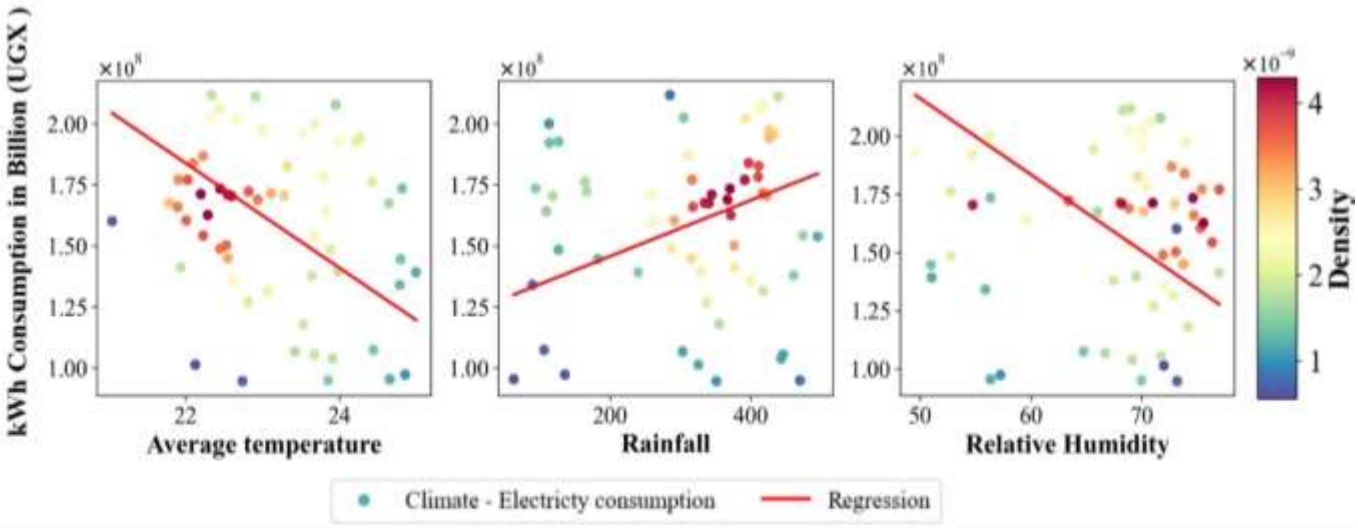


Figure 4.12: Relationship between climate variables and IEC

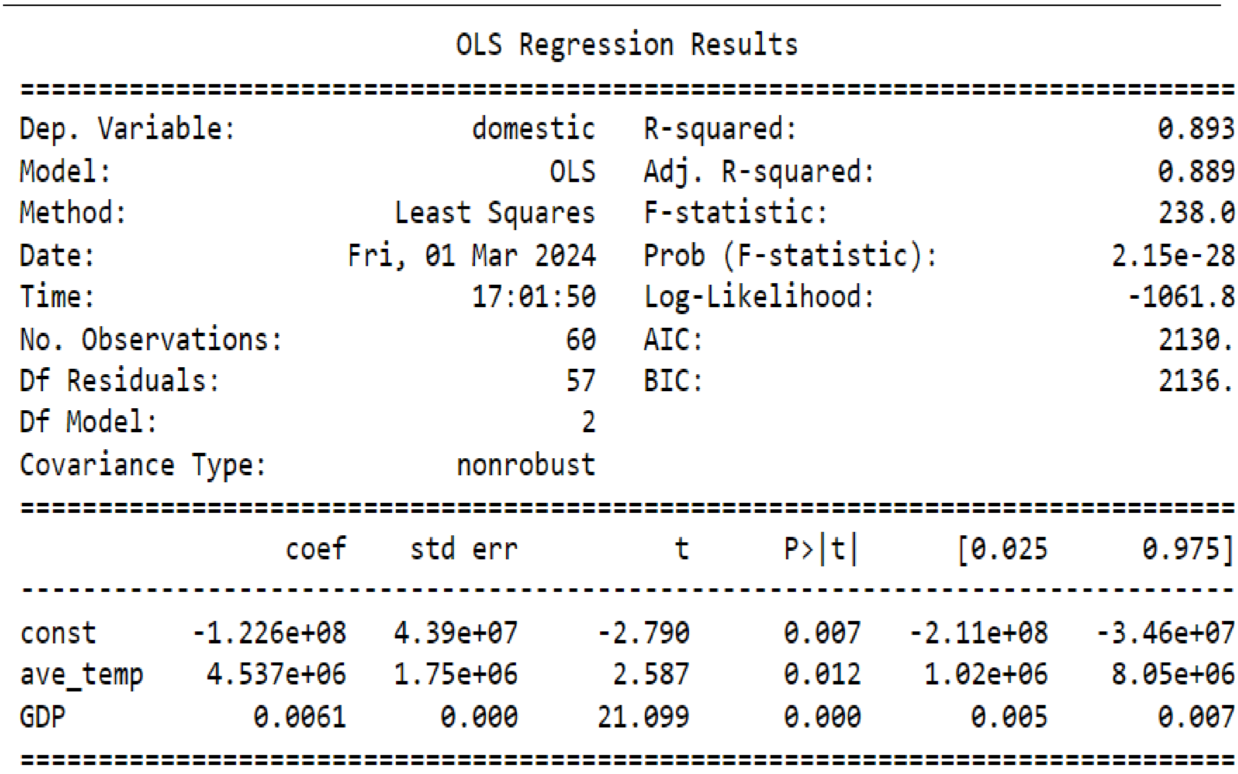
Overall, the first MLR model suggests that climate variables such as average temperature, rainfall, and relative humidity have statistically significant associations with DEC, CEC and IEC. Additionally, the Mean Absolute Percentage Errors (MAPE) for predicting DEC, CEC and IEC (table 4.3) were 20.3%, 20.6% and 17.31% respectively. Meaning that, on average, the model's predictions deviate from actual DEC, CEC and IEC by approximately 20.3%, 20.6% and 17.31%. While the model explains a portion of the variance in electricity consumption, this level of error indicates that other factors not captured by the model may also influence DEC, CEC and IEC. However, looking at the coefficients, out of the three climatic variables, rainfall and relative humidity revealed the least influence on electricity consumption for all sectors in Uganda from 2008 to 2022. Therefore, the study eliminated rainfall and relative humidity from the second model and incorporate the socioeconomic factor of GDP.

4.3.2 Average temperature and Gross domestic product

The second model offers enhanced explanatory and predictive capabilities, highlighting the inclusion of socioeconomic factor of GDP as a relevant predictors and refining model specifications to improve the accuracy of electricity consumption prediction.

Domestic electricity consumption (DEC)

The results show that the coefficient for average temperature is 4.537e+06, indicating a statistically significant positive relationship with actual DEC at 0.05 significant level. Suggesting that for each one-unit increase in average temperature, holding GDP constant, domestic electricity consumption is estimated to increase by approximately 4.537e+06 units. This suggests that warmer temperatures lead to higher electricity usage in households. Looking at GDP, the coefficient also reveals a statistically significant positive impact on DEC, signifying that a one unit a one-unit increase in GDP results in an increase in DEC by approximately 0.0061 units, holding average temperature constant. This was displayed in figure 4.14 where both variables have a positive regression slope but GDP had a stronger relationship with DEC. The observed relationship exhibits statistical significance at 95% confidence level (0.05 significant level). This shows that the variables (average temperature, and GDP) are statistically significant in explaining the variation in DEC in Uganda for the study period. The R-squared value is 0.893, approximately 89.3%, which is an improvement compared to the first model’s (0.229).



```
                            OLS Regression Results
==============================================================================
Dep. Variable:               domestic   R-squared:                       0.893
Model:                            OLS   Adj. R-squared:                  0.889
Method:                 Least Squares   F-statistic:                     238.0
Date:                Fri, 01 Mar 2024   Prob (F-statistic):           2.15e-28
Time:                        17:01:50   Log-Likelihood:                -1061.8
No. Observations:                  60   AIC:                             2130.
Df Residuals:                      57   BIC:                             2136.
Df Model:                           2
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const      -1.226e+08   4.39e+07     -2.790      0.007   -2.11e+08   -3.46e+07
ave_temp    4.537e+06   1.75e+06      2.587      0.012    1.02e+06    8.05e+06
GDP            0.0061      0.000     21.099      0.000       0.005       0.007
==============================================================================
```

Figure 4.13: Multilinear regression results for the relationship between temperature/GDP and DEC in Uganda from 2008 to 2022

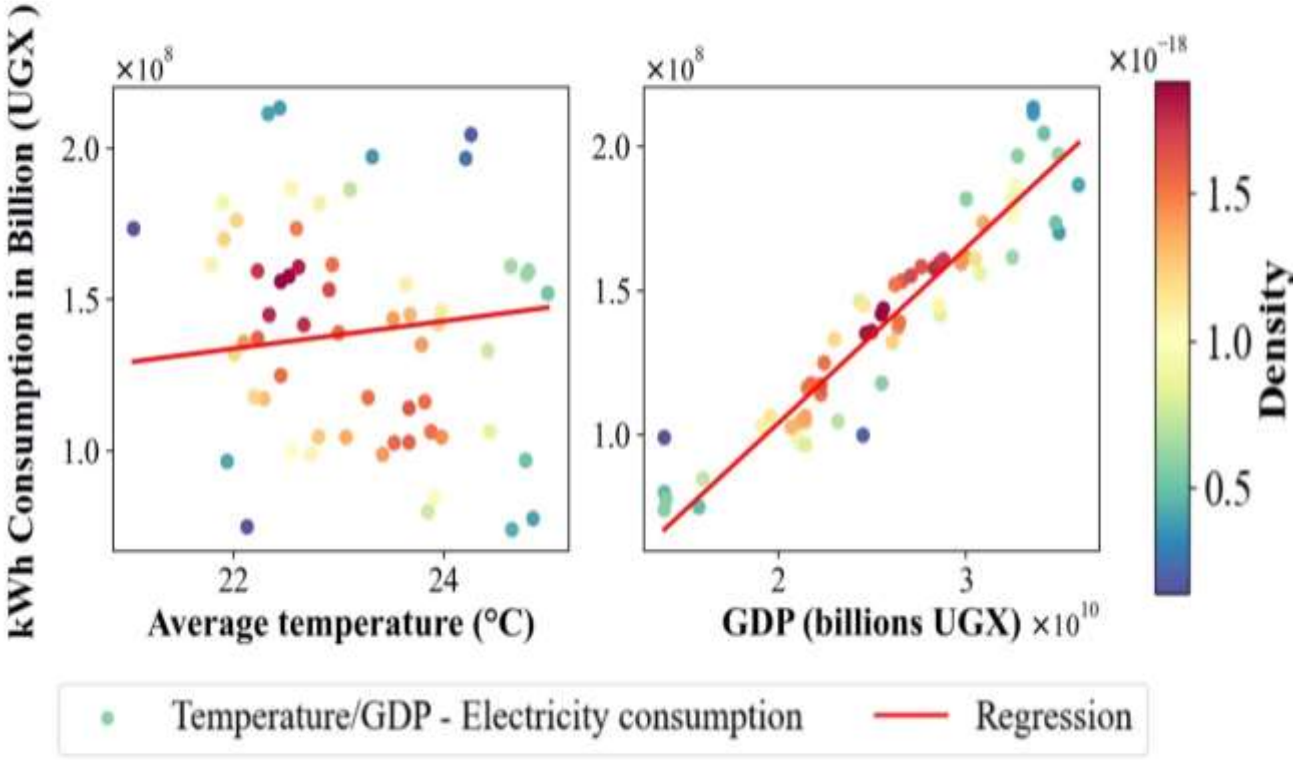


Figure 4.14: Relationship between temperature / GDP and DEC

Historical consumption vs Modelled DEC

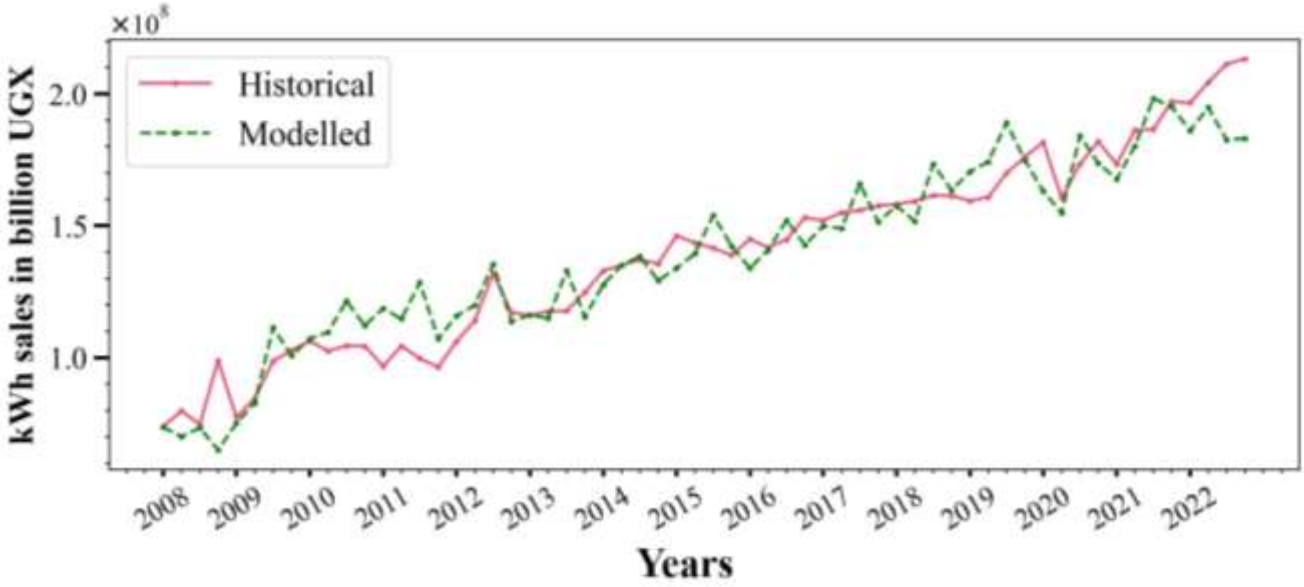
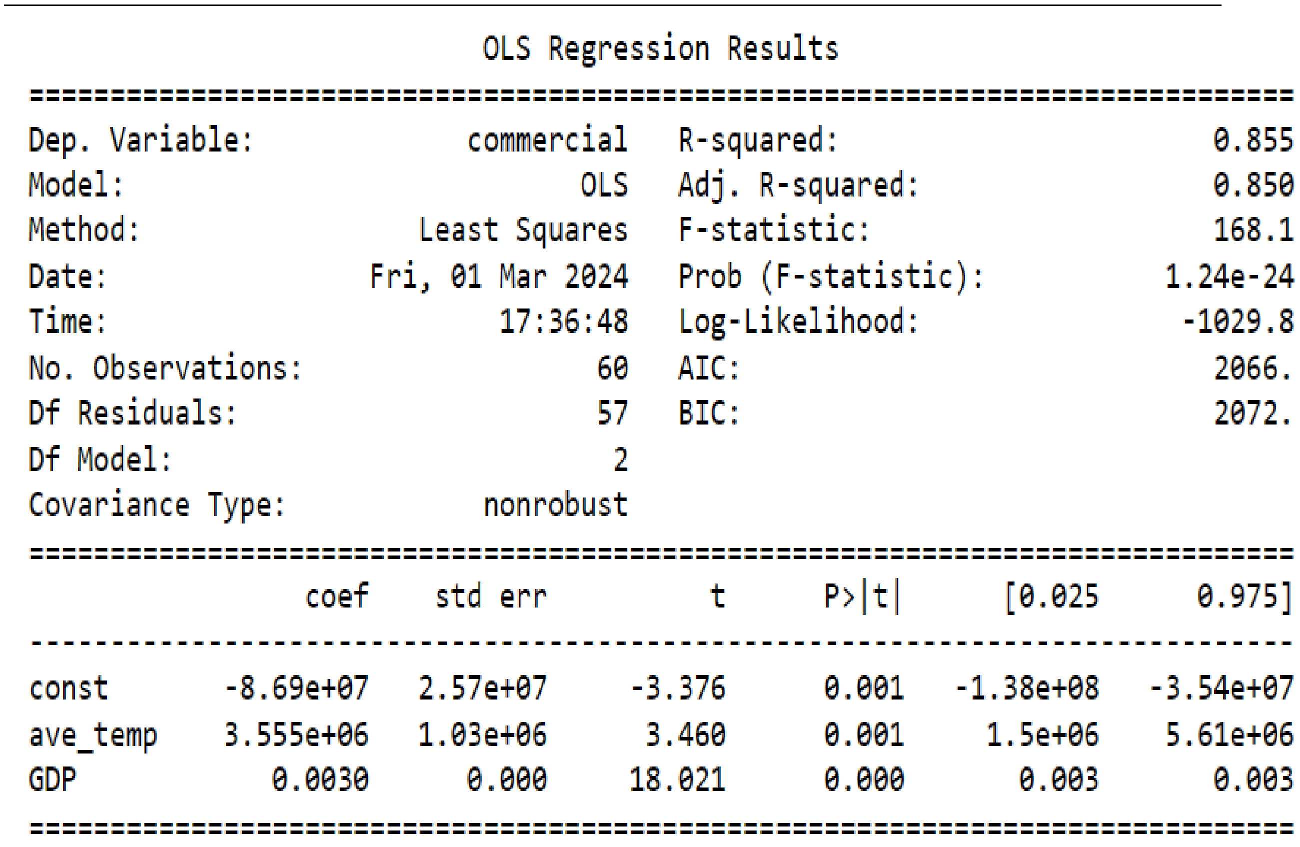


Figure 4.15: Timeseries of historical and modelled quarterly DEC in Uganda.

Commercial electricity consumption (CEC)

A similar relationship (figure 4.17) is observed as in DEC, that is, for every unit increase in average temperature, CEC tends to increase by approximately 3.555e+06 units. Similarly, for every unit increase in GDP, commercial electricity consumption tends to increase by 0.0030 units, assuming all other factors remain constant. The p-values associated with the coefficients are less than 0.05, rendering the relationships statistically significant at 0.05 significant level. However, only two points were lying on the regression line showing a weak relationship between average temperature and CEC. The R-squared is at 0.855 compared to 0.19 in the first model, implying that 85.5% of the variation in CEC is explained by average temperature and GDP.



```
                            OLS Regression Results
==============================================================================
Dep. Variable:             commercial   R-squared:                       0.855
Model:                            OLS   Adj. R-squared:                  0.850
Method:                 Least Squares   F-statistic:                     168.1
Date:                Fri, 01 Mar 2024   Prob (F-statistic):           1.24e-24
Time:                        17:36:48   Log-Likelihood:                -1029.8
No. Observations:                  60   AIC:                             2066.
Df Residuals:                      57   BIC:                             2072.
Df Model:                           2
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const       -8.69e+07   2.57e+07     -3.376      0.001   -1.38e+08   -3.54e+07
ave_temp    3.555e+06   1.03e+06      3.460      0.001     1.5e+06    5.61e+06
GDP            0.0030      0.000     18.021      0.000       0.003       0.003
==============================================================================
```

Figure 4.16: Multilinear regression results for the relationship between temperature / GDP and CEC in Uganda from 2008 to 2022.

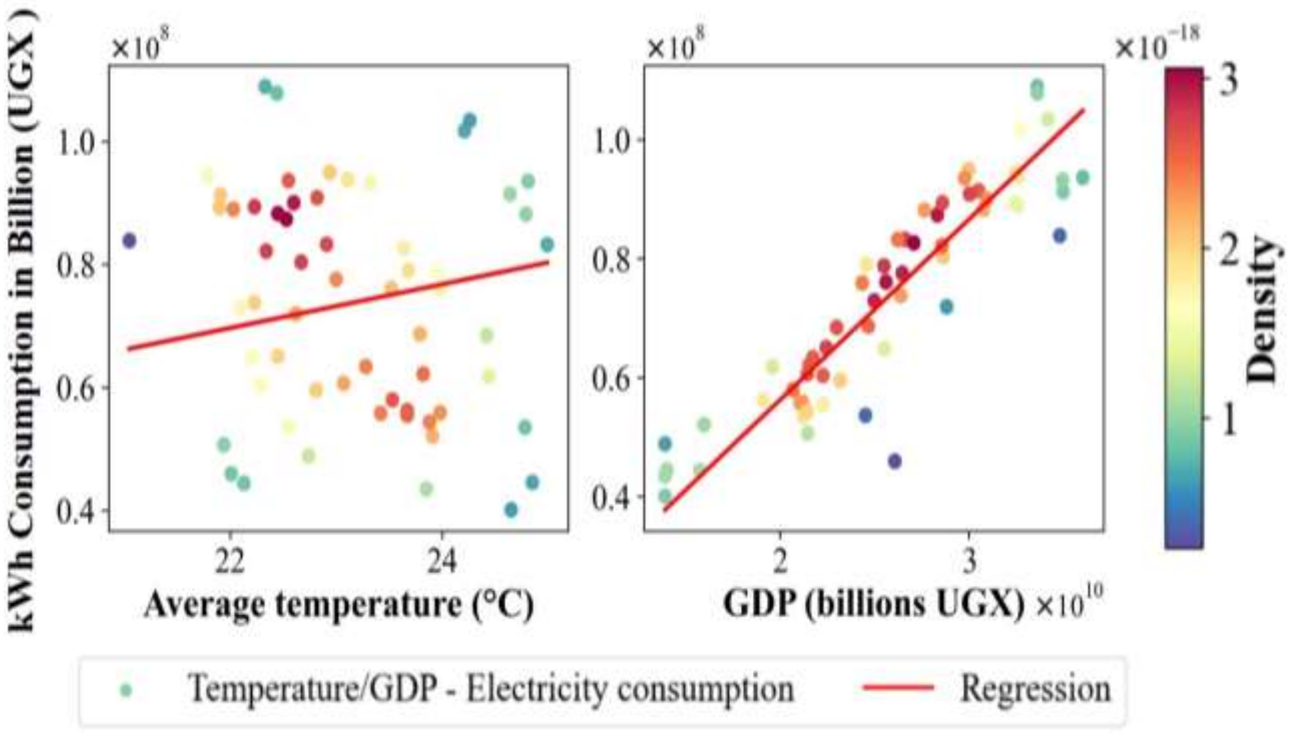


Figure 4.17: Relationship between temperature / GDP and CEC

Historical consumption vs Modelled CEC

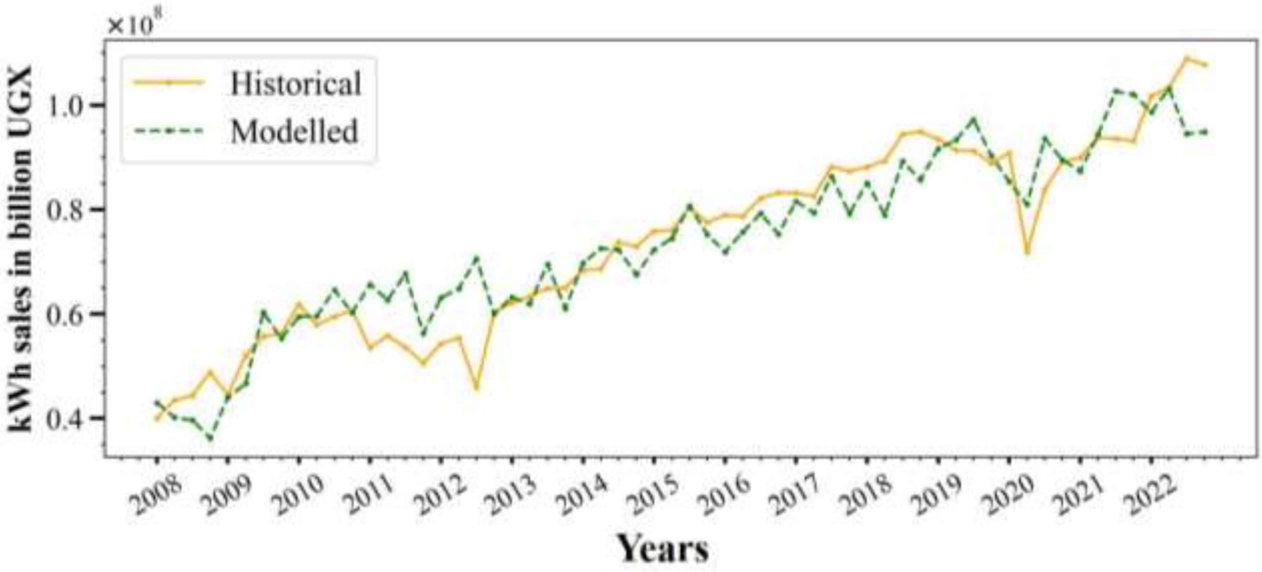
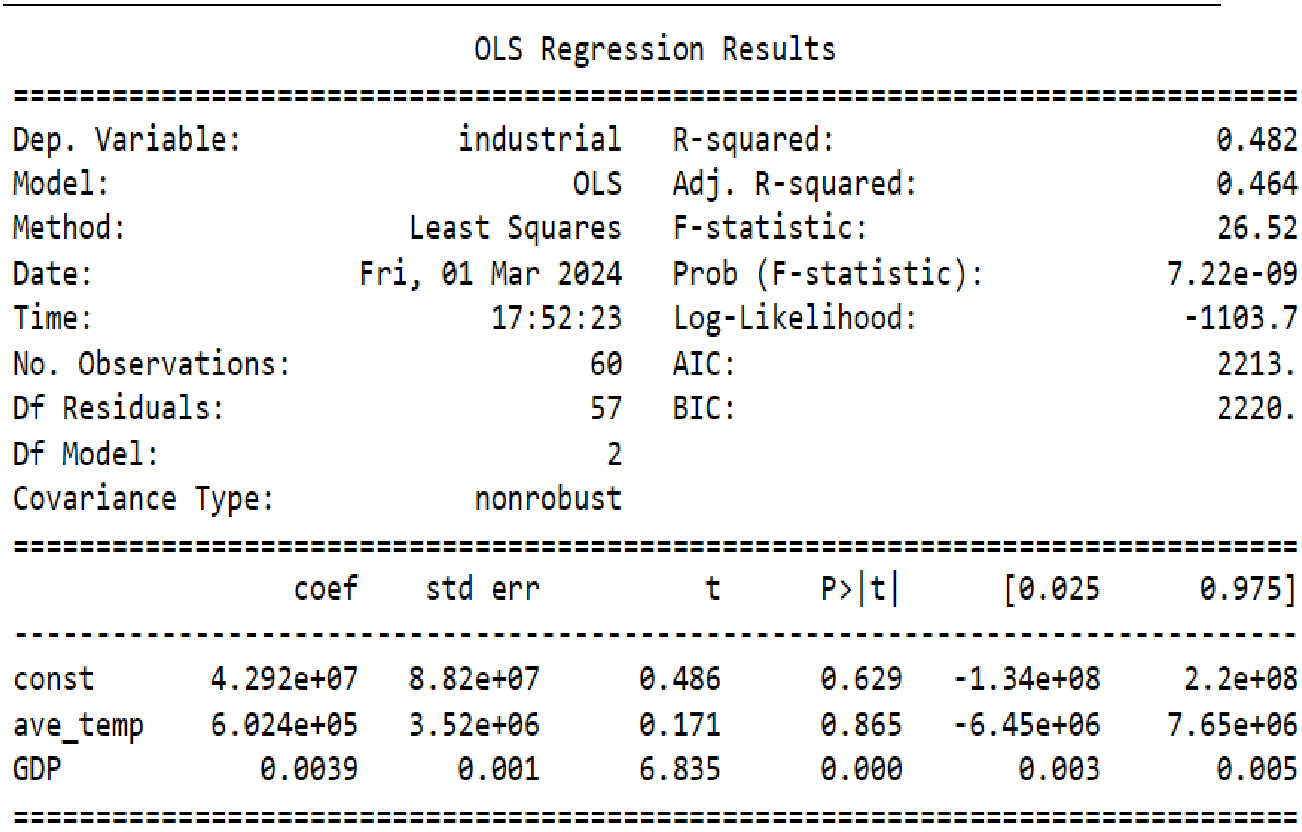


Figure 4.18: Timeseries of historical and modelled quarterly CEC in Uganda

Industrial electricity consumption (IEC)

The relationship between IEC and average temperature and GDP is like that of DEC and CEC, that is, for every unit increase in average temperature, IEC tends to increase by approximately 6.024e+05 units. Similarly, for every unit increase in GDP, IEC tends to increase by 0.0039 units, assuming all other factors remain constant. However, the relationship with average temperature is not statistically significant as the p-value is greater than 0.05 significant level while the relationship with GDP is statistically significant. Meaning the changes in temperature do not have a statistically significant effect on IEC in this model. This was clearly presented in figure 4.20, where average temperature has a horizontal regression line, indicating no relationship with IEC. Although the R-squared of the second model is better than that of the first model, it is relatively low at 0.482 compared to DEC and CEC for the second model, implying that 48.2% of the variation in IEC is explained by average temperature and GDP.



```
                            OLS Regression Results
==============================================================================
Dep. Variable:             industrial   R-squared:                       0.482
Model:                            OLS   Adj. R-squared:                  0.464
Method:                 Least Squares   F-statistic:                     26.52
Date:                Fri, 01 Mar 2024   Prob (F-statistic):           7.22e-09
Time:                        17:52:23   Log-Likelihood:                -1103.7
No. Observations:                  60   AIC:                             2213.
Df Residuals:                      57   BIC:                             2220.
Df Model:                           2
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const       4.292e+07   8.82e+07      0.486      0.629   -1.34e+08     2.2e+08
ave_temp    6.024e+05   3.52e+06      0.171      0.865   -6.45e+06    7.65e+06
GDP            0.0039      0.001      6.835      0.000       0.003       0.005
==============================================================================
```

Figure 4.19: Multilinear regression results for the relationship between temperature/GDP and IEC in Uganda from 2008 to 2022

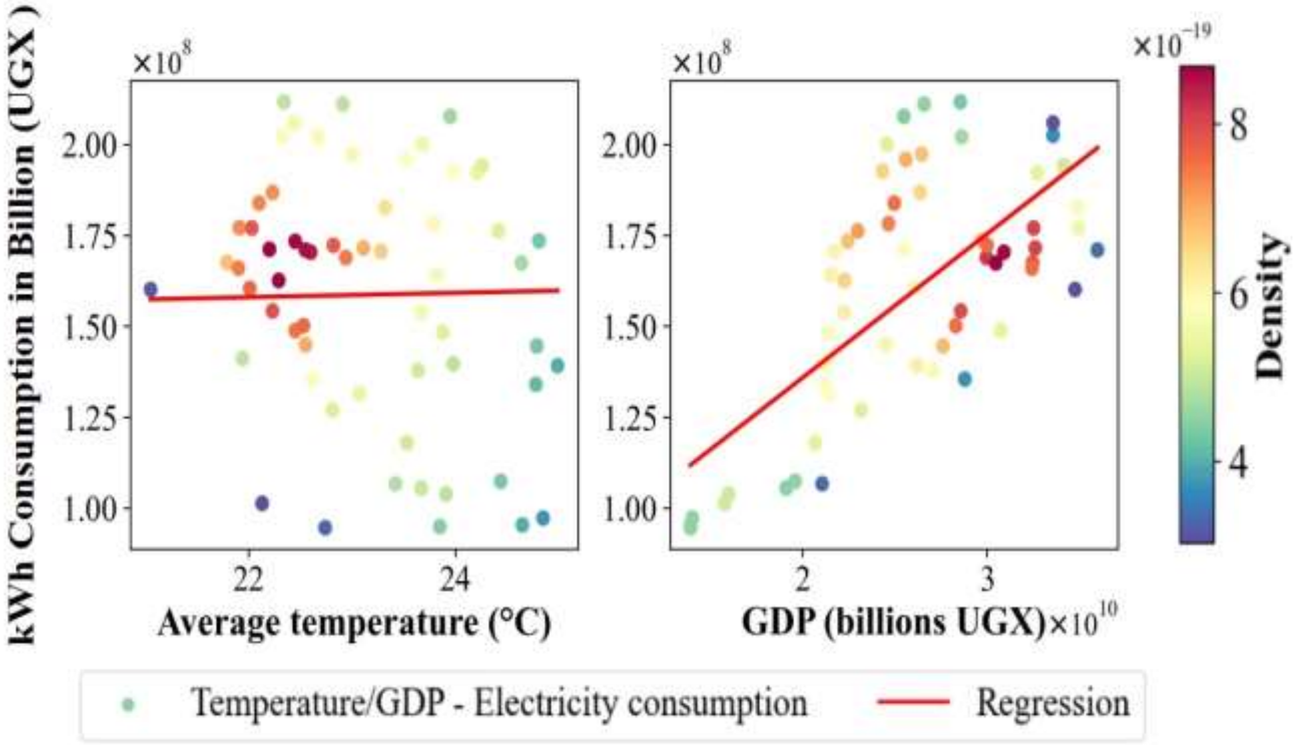


Figure 4.20: Relationship between temperature / GDP and IEC

Historical consumption vs Modelled IEC

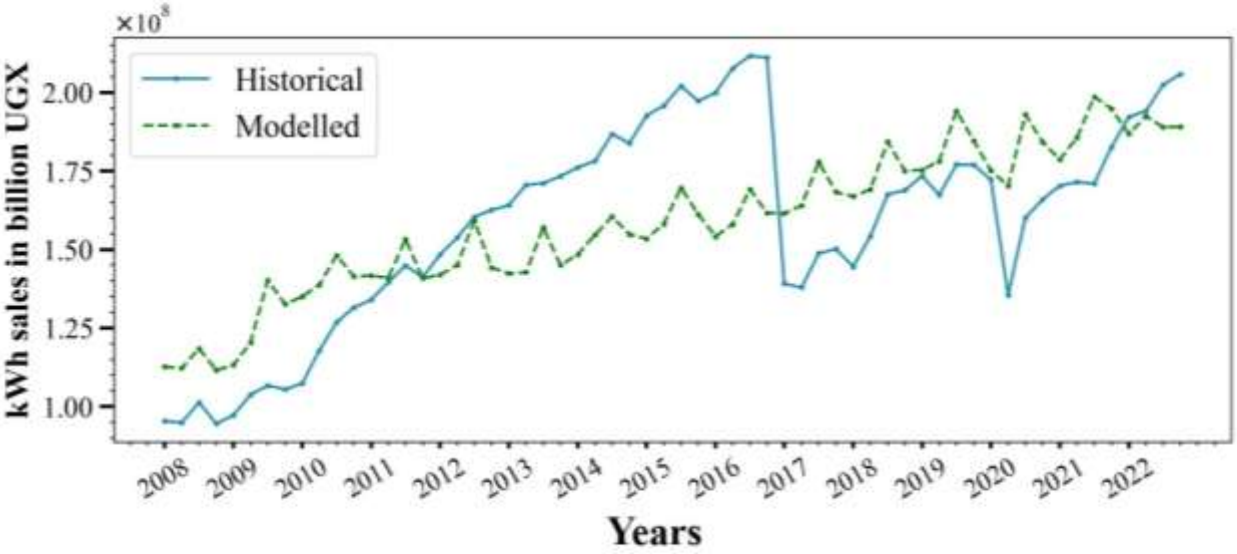


Figure 4.21: Timeseries of historical and modelled quarterly IEC in Uganda

The introduction of GDP as a predictor in the second model provides additional explanatory power, contributing to a more comprehensive understanding of DEC, CEC and IEC patterns. While GDP appears to be a significant predictor of IEC, temperature does not show a significant effect in this model. This suggests that factors other than temperature may play a more dominant role in influencing IEC patterns. The lower MAPE values of 6.66%, 7.67% and 13.02%, in the second model suggest improved predictive performance compared to the first model, indicating that the revised model provides more accurate predictions of DEC, CEC and IEC. The big MAPE error for IEC shows that the model does not perform well in predicting IEC.

Table 4.0.3: Evaluation results of Multilinear regression model (1 and 2)

Dependent variable (kWh)	**Model (1)**		**Model (2)**	
	Temp, Rainfall, RH		**Temp, GDP**	
	R^2	**MAPE**	**R^2**	**MAPE**
Domestic	0.23 (23%)	20.3%	0.893 (89.3%)	6.7%
Commercial	0.19 (19%)	20.6%	0.855 (85.5%)	7.7%
Industrial	0.17 (17%)	17.3%	0.482 (48.2%)	13.0%

4.4 Future impact of climate variability on electricity consumption

Drawing from the results of the current relationship between climate variables and electricity consumption, the combined effect of average temperature and GDP showed better performance in prediction or explaining the variation in DEC and CEC patterns. To investigate the future impact of average temperature and GDP on electricity consumption, the study used the mean model ensemble (MME) of three RCMs to depict the future projections under SSP2.6 and SSP8.5 scenarios in order to demonstrate the future changes in temperature. For the future analysis, GDP is assumed not to change.

4.4.1 Evaluation of Regional climate model

Figure 4.22 shows the results of the performance of the mean ensemble of RCM models against observed temperature data. The evaluation displays relatively good performance over the study area. That is, the correlation coefficient shows 0.84 with observed data, while the Root Mean Squared Difference (RSMD) depicts a low magnitude < 50%. Moreover, a relatively low standard deviation about 0.65^0C is simulated against the observed value of 0.80^0C. The results agree with studies that used the same criteria to evaluate model performance in reproducing climate data across sub-Saharan Africa against station data (Ayugi et al., 2021; Ngoma et al., 2021).

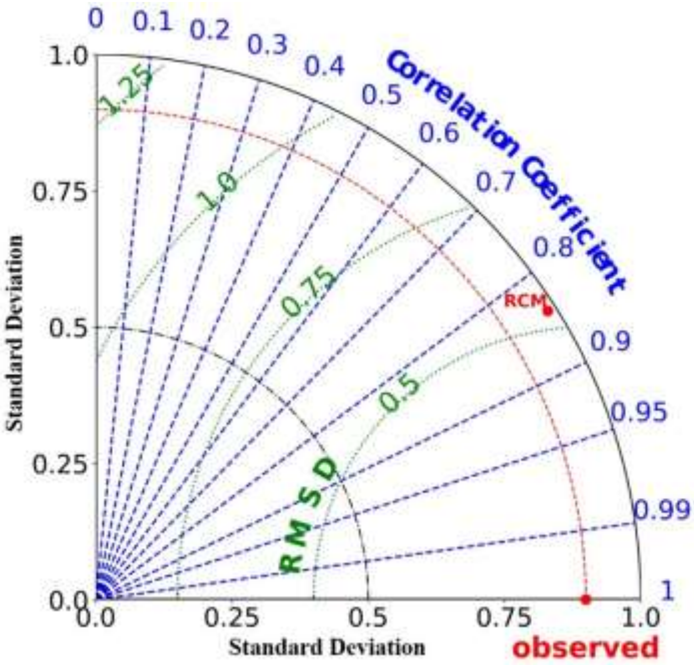


Figure 4.22: Taylor diagram showing the performance of mean RCM model against observed temperature

4.4.2 Bias correction of future simulations

The bias correction technique applied is Quantile Mapping (QM) with linear mapping. The principle of QM technique relies on adjusting the cumulative distribution functions (CDF) of the simulated future RCM data based on observed historical data. This method matches the CDF of the simulated future RCM data and the observed historical data together thereby correcting the bias (extremes, intensity and frequency) (Boonwichai et al., 2018). It has been proven that the quality of RCM data and shape of CDF is improved through QM. Quarterly observed and simulated temperature data from 2008 – 2022 (15 years) were used to bias correct the future simulated data (2023 – 2060). QM technique was able to improve the CDFs of the RCM data as shown in figure 4.23. They show that the RCM was overestimating for both scenarios before bias correction.

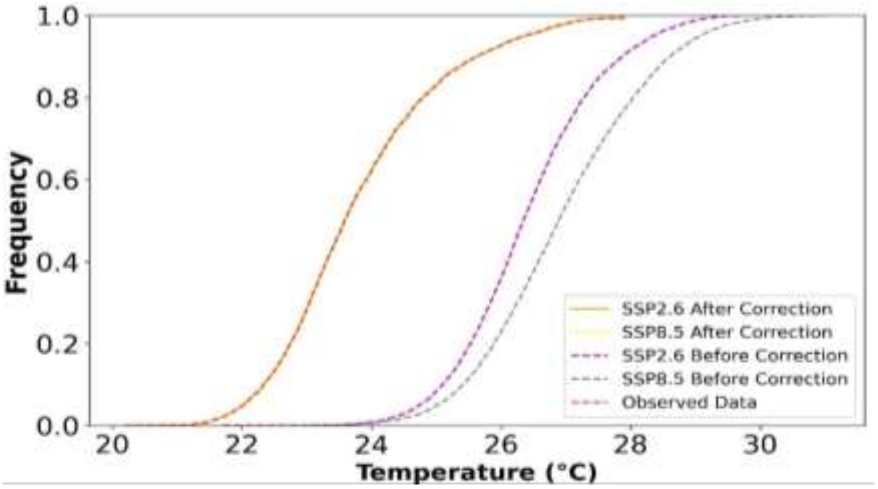


Figure 4.23: Quantile mapping bias correction of future RCM model temperature

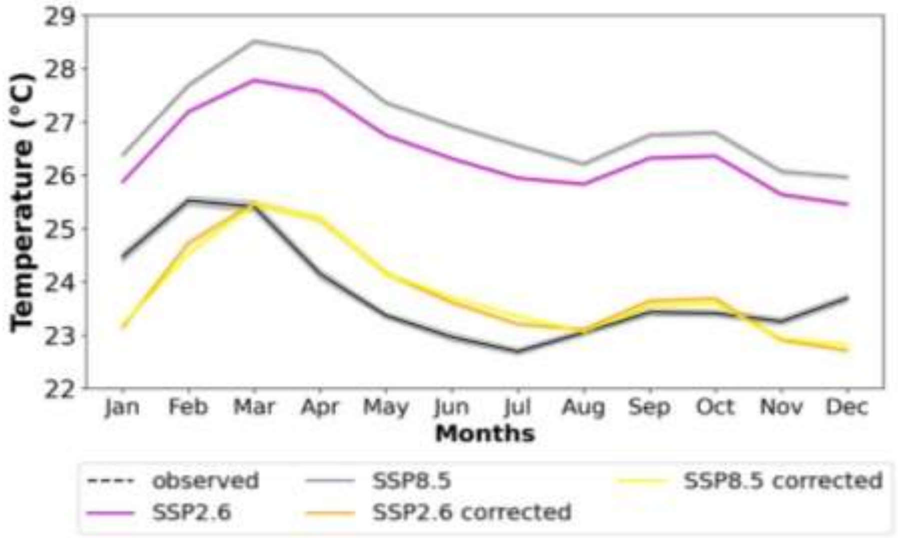


Figure 0.24: Monthly distribution of future temperature for both corrected and raw SSP2.6 and SSP8.5 scenarios over Uganda

4.4.3 Future trends in temperature

The temporal distribution of corrected future average temperature under scenarios SSP2.6/8.5 is represented in figure 4.25 against the historical temperature for Uganda.

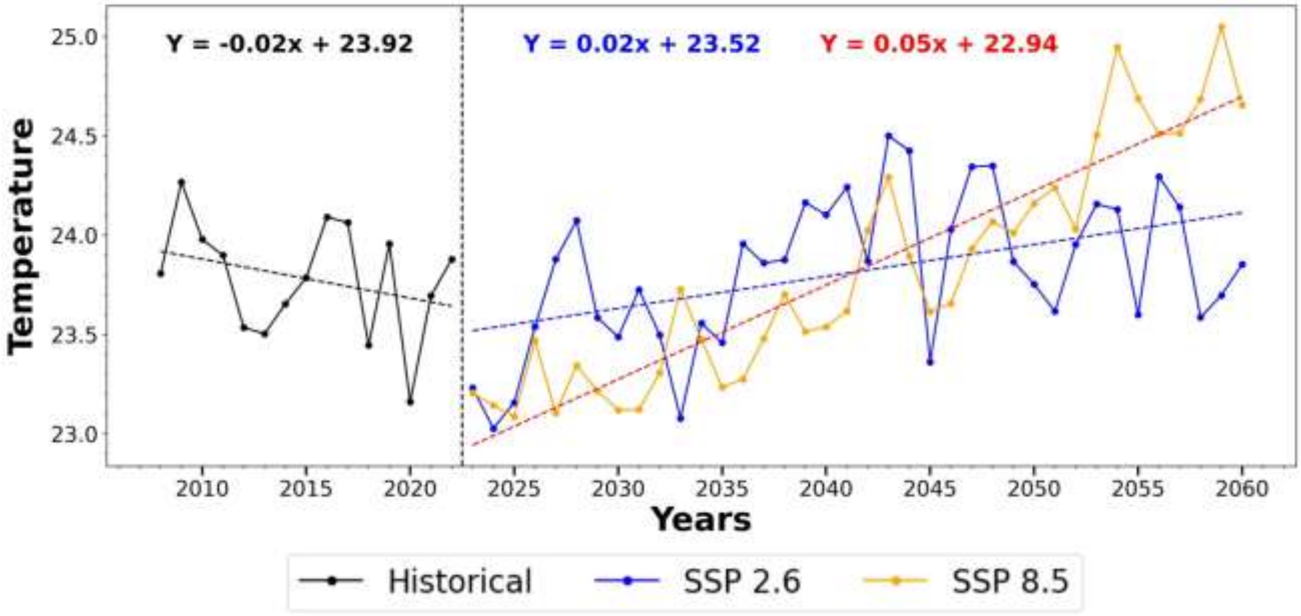


Figure 4.25: Timeseries of historical and future temperature under SSP2.6 and SSP8.5 over Uganda.

Figure 4.25, indicates a relatively decreasing historical average temperature trend over the past decade and a half. Temperatures fluctuate slightly from year to year but generally hover around the mid-20^0C. Under SSP2.6, which represents a scenario of rapid decarbonization and strong climate policies, average temperature in Uganda is projected to increase gradually but at a slower rate starting around 23°C in 2023 and reach approximately 24°C by 2060. The rate of increase is relatively steady with some minor fluctuations, indicating a more controlled climate change scenario in Uganda over the coming decades compared to SSP8.5. In contrast, SSP8.5 represents a high-emission scenario with limited climate action. Here, average temperature shows a more pronounced upward trajectory starting slightly lower than SSP2.6 in 2023 and gradually accelerates over time. This indicates a faster rate of temperature rise compared to SSP2.6.

Both future scenarios depict a notable departure from historical temperature trends. While historical data showed relatively stable temperatures, both SSP2.6 and SSP8.5 project consistent warming over the next few decades. This suggests that climate change will likely exert a more significant influence on Uganda's temperature dynamics in the future. Furthermore, the difference between SSP2.6 and SSP8.5 highlights the critical role of mitigation efforts and climate policies. Under SSP2.6, where stronger measures are taken to limit emissions, the rate of temperature increase is slower compared to SSP8.5. This underscores the importance of implementing sustainable practices and policies to mitigate the impacts of climate change. The projected temperature increases could significantly affect

Uganda's electricity consumption. Higher temperatures may lead to increased demand for cooling, particularly in urban areas, putting additional strain on the electricity grid.

4.4.4 Future relationship between temperature, GDP and electricity consumption

The future impact of temperature on electricity consumption in Uganda is presented in figures 4.26, 4.27, 4.28 and 4.29 The second model was used to simulate the future relationship using projected average temperature under SSP2.6 and 8.5 and GDP was assumed to be constant. The future analysis was categorized into future 1 (2023 – 2037) and future 2 (2038 – 2052) for electricity consumption in the domestic and commercial sectors. The Industrial sector was not included in the future analysis because it revealed no relationship.

Domestic electricity consumption (DEC)

Future 1 (2023 – 2037)

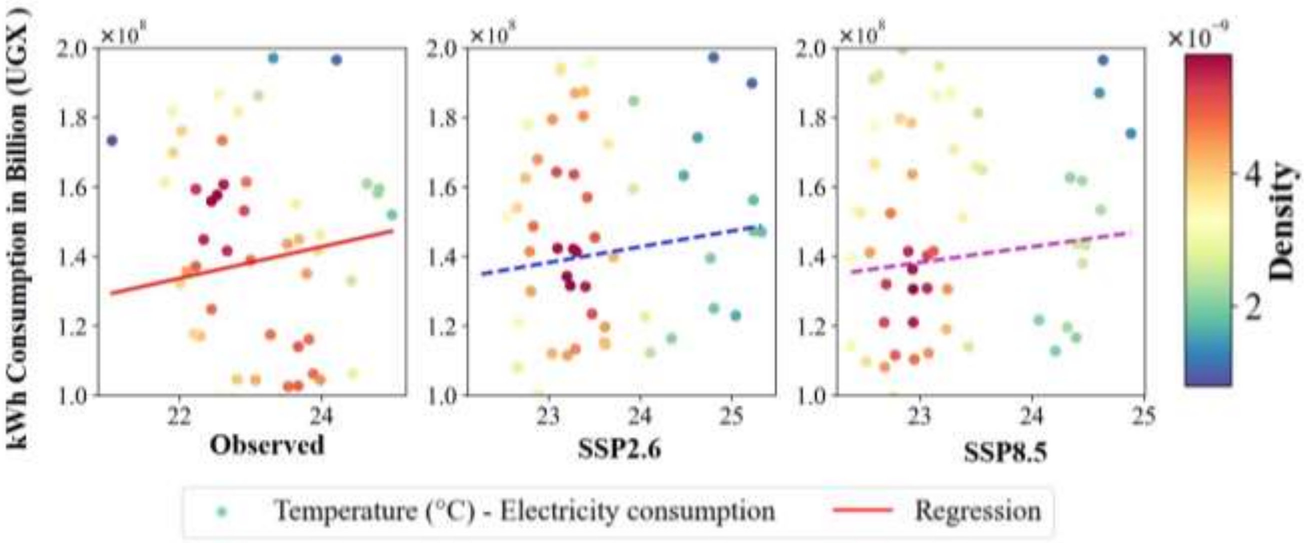


Figure 4.26: Relationship between historical / future temperature and DEC from 2023 to 2037

Future 2 (2038 – 2052)

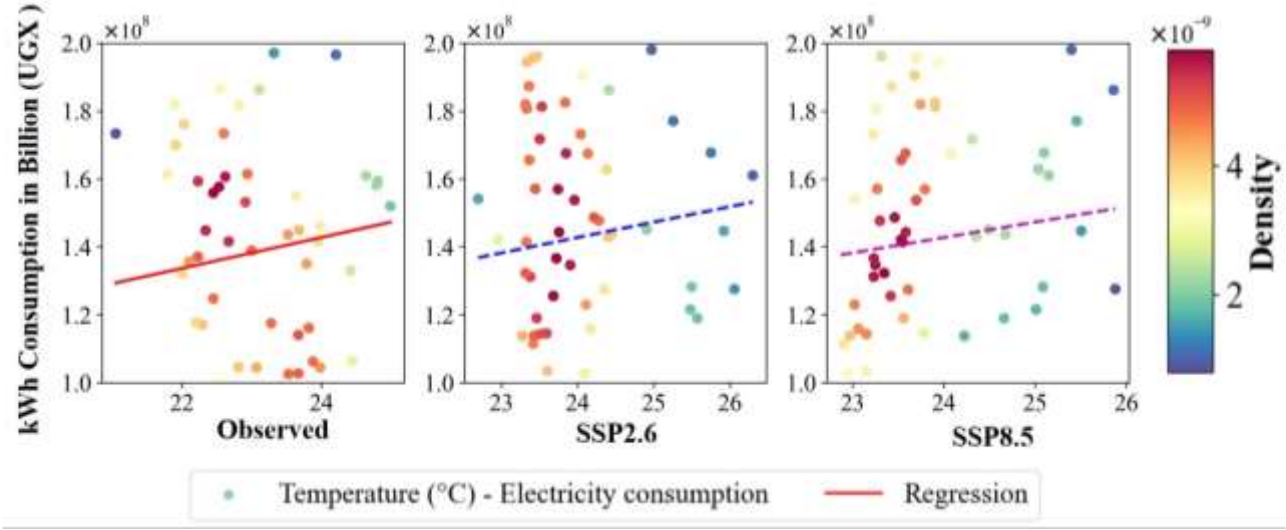


Figure 4.27: Relationship between historical / future temperature and DEC from 2038 to 2052

The regression slopes in both future periods (fig x and y) demonstrate a positive correlation between temperature and DEC, indicating that as temperature increases, DEC also increases. However, the degree of this increase varies slightly between scenarios. In both future scenarios 1 and 2, the observed DEC increased from UGX 1.3x10^8 to 1.38x10^8 kWh billion under both SSP scenarios, representing an approximate increase of UGX 0.08x10^8 kWh billion. serves as an indicator of the likelihood of a temperature-DEC correlation. Red points indicate areas of higher DEC, potentially signifying higher consumption, while green/blue points represent lower density, indicating lower DEC. The clustered distribution of points shows that there is a higher likelihood of correlation between temperature and DEC while sparse distribution indicates lower likelihood. The observed temperature-DEC relationship is prominent within the temperature range of 22 to 24°C. This suggests instances where DEC is relatively high compared to other temperature ranges, possibly due to factors such as increased use of cooling systems. However, in the future scenarios, there is a noticeable shift in DEC patterns compared to historical trends, where the concentration of data points lies between 23 to 24°C and 23°C under SSP2.6 and SSP8.5 scenarios, respectively. The density of concentration increases in future scenario 2 compared to future scenario 1. This shift could be attributed to socio-economic changes leading to slightly different DEC behaviors in response to temperature changes. Furthermore, the points lying on the regression line suggest that at these specific temperature points, there is a significant influence on the overall trend in DEC in Uganda.

Commercial electricity consumption (CEC)

Future 1 (2023 – 2037)

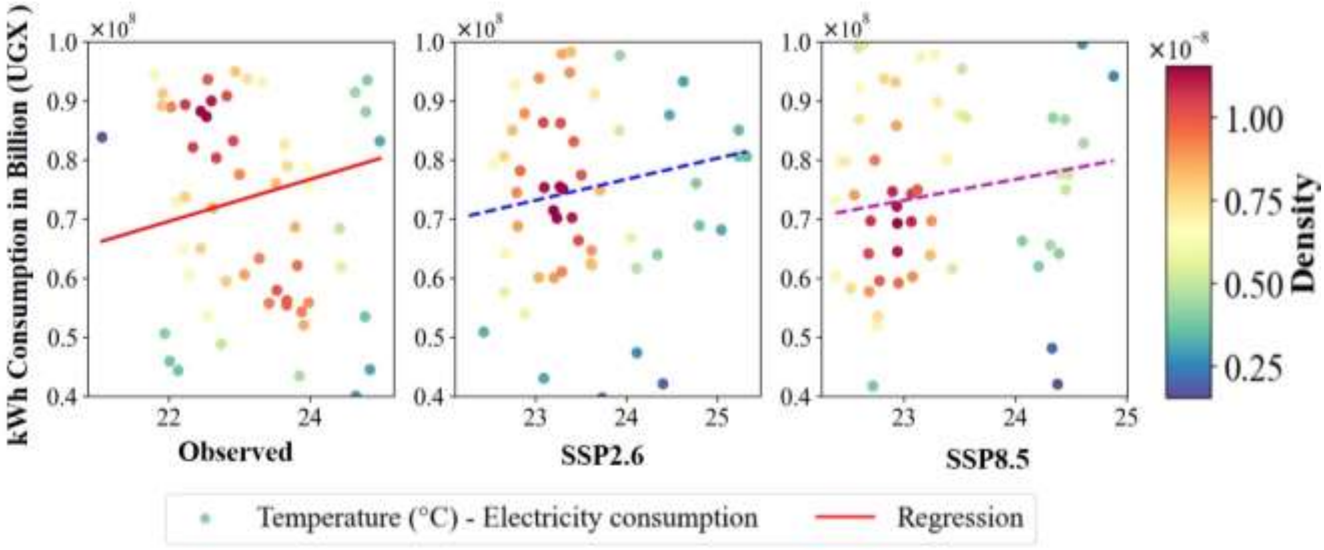


Figure 4.28: Relationship between historical / future temperature and CEC from 2023 to 2037

Future 2 (2038 – 2052)

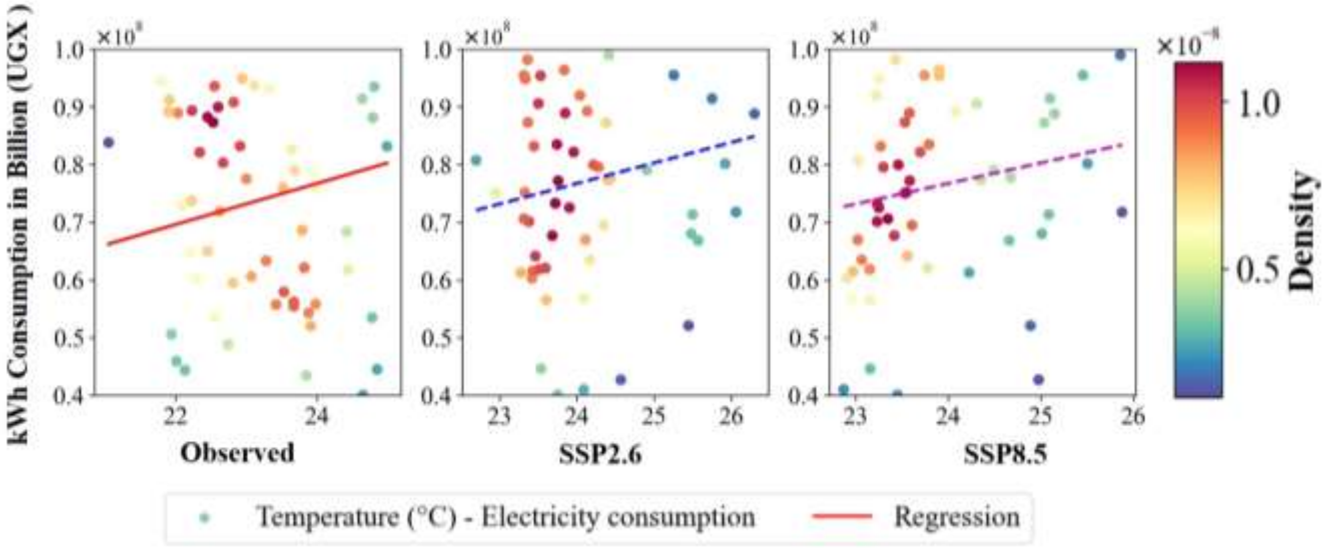


Figure 4.29: Relationship between historical / future temperature and CEC from 2038 to 2052

The future analysis for CEC yields similar results to the domestic sector. Like DEC, there exists a positive relationship between temperature and CEC in both future 1 and 2 scenarios, indicating that as temperature rises, so does CEC. Figure 4.29 illustrates an observed increase in CEC from UGX 0.67x10^8 to 0.71x10^8 kWh billion under both SSP scenarios, reflecting an approximate rise of UGX 0.04×10^8 kWh billion. Moreover, the distribution of data points concentrates within similar temperature ranges for both historical and projected scenarios. However, with only two points lying on the regression line there appears to be a relatively weaker correlation between temperature and CEC in the observed relationship compared to the future relationship under both SSP scenarios. This observation suggests that as we move into future scenarios under varying socioeconomic and climatic conditions, the relationship between temperature and electricity consumption may become more evident and possibly stronger compared to the current scenarios.

4.5 Discussion and Implication

The analysis of climate variability over the period from 2008 to 2022 has uncovered fluctuations in rainfall, temperature, and relative humidity. This fluctuation pattern underscores the reality of climate variability in Uganda, characterized by changing temperatures and altered rainfall patterns (Babyenda et al., 2023). Given Uganda's heavy reliance on hydropower, which accounts for 80% of its electricity supply (Twinomuhangi et al., 2022a), such variability in climatic conditions could potentially disrupt electricity generation, supply, and demand. The increased rainfall experienced in 2019, particularly over Lake Victoria, led to a rise in water levels, posing challenges to electricity generation as floating vegetation obstructed water flow to hydro power stations on the Nile in Jinja. For instance, on April 14th 2020, there was a national black out after a floating island docked at the Nalubale power dam blocking water for power generation (Eskom, 2020).

The sectoral electricity consumption for the study period shows an upward trend in all sectors in Uganda. This surge, particularly in DEC, reflects Uganda's commitment to achieving universal electrification of households as outlined in the National Development Plan III (NDP III) (National Planning Authority, 2020). This reflects on the improved standards of living as households gain access to electricity, facilitating urbanization in Uganda. As households gain access to electricity, they are afforded opportunities for improved lighting, cooking, and various other essential services, thereby bettering overall quality of life metrics. Rural communities in Uganda also have a genuine need for electricity to pump water, transport commodities, engage in income-generating activities, practice modern healthcare, and extend work and leisure hours (Kirabo & Faustino, 2023). Furthermore, electricity consumption within the domestic sector serves as a noticeable indicator of heightened electrification efforts across Uganda. The free electricity connection policy has played a significant role in improving access to electricity in Uganda (Sebyala, 2020). Moreover, the upward trends in Commercial Electricity Consumption (CEC) and Industrial Electricity Consumption (IEC) signal thriving businesses, industrialization, and economic expansion in Uganda (Okello-Obura & Muzaki, 2015; Appiah et al., 2019). The correlation between GDP and electricity consumption (Sekantsiand & Motlokoa, 2015) highlights the heightened economic development during the study period in Uganda. The corresponding variations in GDP and electricity consumption could be influenced by factors like population growth, technology advancements, shifts in consumer behavior and most recently COVID19 pandemic (Kizza et al., 2023).

The objective of the study was to investigate whether climate variability influenced electricity consumption patterns in Uganda from 2008 to 2022. Analysis using two Multiple Linear Regression (MLR) models revealed significant associations between climate variables and DEC, CEC, and IEC. The first model, focusing on average temperature, rainfall, and relative humidity, highlighted the role of temperature in shaping electricity consumption patterns. The model showed a negative relationship between temperature/relative humidity and electricity consumption across all sectors, indicating that as temperature increases/decreases, electricity consumption decreases/increases, respectively. As the temperature rises, the cooling processes become less effective, leading to a decrease in efficiency (Zamanipour et al., 2023). Moreover, higher temperatures can also cause power plants to experience more frequent shutdowns, further reducing their capacity, thereby affecting consumption. Meanwhile, a positive relationship was revealed for rainfall and electricity consumption in all sectors, implying that an increase in rainfall tends to correspond to higher electricity consumption. Although, rainfall and relative humidity contribute to explaining the electricity consumption variability, their influence in Uganda is comparably weaker than that of temperature. Bonkaney, (2020) found similar results about the influence of precipitation on electricity consumption. The influence of relative humidity on electricity consumption is documented to be more pronounced in areas where it varies greatly throughout the year, like in the Sahel regions (Kondi-Akara et al., 2023). However, the performance of the first model was limited by high MAPE and low R-squared values, implying that, while the model captures a portion of variation in electricity consumption, there are other factors not accounted for that influence electricity consumption patterns. Thus, the study refined the model by removing rainfall and relative humidity and incorporating GDP as a socioeconomic factor. The addition of GDP allows a comprehensive assessment of electricity consumption (Gallo Cassarino et al., 2018; Zheng et al., 2020) for all sectors in a socioeconomic environment. The second model, enhanced with GDP, exhibited improved performance metrics, with improved values of R-squared and MAPE compared to the first model. Positive relationships between temperature and electricity consumption were observed in all sectors except for the industrial sector. This aligns with findings from Ghana, where temperature fluctuations positively impacted residential electricity demand (Kazeem et al., 2022). As noted by (Ahmed et al., 2012), electricity consumption tends to increase with both low and high temperatures due to heating and cooling requirements, respectively. Meanwhile, the effect of temperature was not significant in influencing IEC, and the, highlighting a complexity of IEC dynamics in Uganda.

Future projections under different scenarios (SSP2.6 and SSP8.5) from 2023 to 2060 depict notable deviations in temperature trends compared to the observed stable patterns from 2008 to 2022. Under SSP2.6, characterized by rapid decarbonization and strong climate policies, temperatures are projected to increase gradually but at a slower rate compared to SSP8.5. In contrast, SSP8.5, representing a high-emission scenario with limited climate action, shows a more pronounced upward trajectory in temperature rise. Temperature increase can influence electricity consumption positively or negatively. According to the Stern Report, a temperature rise of 3-6°C in the coming years may lead to a significant decrease in water availability by 30–50% (Stern, 2007). This reduction in water resources could potentially disrupt hydro energy supply, change energy demand patterns, and cause damage to energy infrastructure (Ebinger & Vergara, 2011). Ndayishimiye et al. (2022) linked the projected decrease in total electricity production in Uganda to the decline in Lake Victoria water levels as a result of increase in surface temperature. Furthermore, a notable decline in electricity generation occurred at a hydro-power plant on the Mpanga river in Western Uganda, particularly during extended dry spells or drought conditions (Markandya et al., 2015). Positively, an increase in temperature increases demand for cooling, air conditioning and refrigeration. The results reveal a positive relationship between temperature and electricity in both future 1 and future 2 scenarios. For example, findings demonstrate a direct correlation between temperature and electricity consumption in both anticipated future scenarios. This pattern is not unique to Uganda but is observed worldwide, including in African nations, where rising temperatures necessitate increased reliance on cooling technologies (Karimu & Mensah, 2015; Bonkaney, 2020). As a result, there was a projected increase in electricity consumption of approximately UGX 0.08 x10^8 and 0.04 x10^8 billion (kWh) in domestic and commercial sectors respectively. Due to the current low penetration of air conditioners in Uganda, the impact of temperature variability on electricity consumption is minimal. Nevertheless, air conditioning usage is projected to grow by approximately 5.10% between 2024 and 2028 (Statista Market Insights, 2023), and is attributed to the growth of commercial and residential sectors (Medard, 2019). As we progress in future, the influence of temperature on electricity may become more evident and stronger compared to the past.

4.6 Limitations of the study

Some limitations are evident in this study, which warrant consideration. The limited availability of electricity consumption data constrained the analysis to only 15 years, conducted on a quarterly basis for Uganda. This limited temporal scope may not fully capture the complex electricity consumption patterns relative to climate variability over longer periods. Additionally, the use of quarterly data overlooks the intra-annual variations in electricity consumption. Given the dynamic interplay between climate fluctuations and electricity consumption, there’s need to aggregate system dynamic analysis to capture the underlying factors that contribute to electricity consumption in relation to climate. Furthermore, given the complex climatic patterns in Uganda, it is possible that the electricity consumption varies from one region to another. Therefore, a region-specific study is needed to improve the analysis in order to implement tailored electricity consumption policies for effective planning and management. Given these limitations, the results of this study serve as a preliminary investigation, providing a basis for further research endeavors. Future studies could employ more extensive datasets encompassing longer timeframes.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

This chapter provides a brief summary of the results that were drawn from the various analyses carried out in this study. It similarly highlights the major conclusions that were obtained from the study as well as suggesting recommendations.

5.1 Conclusion

The analysis conducted on climate variability in Uganda spanning from 2008 to 2022 highlights the dynamic nature of the country's climate system. Through assessing of temperature, rainfall, and relative humidity data, distinct patterns and fluctuations were identified, revealing both moderate fluctuations and extreme anomalies. The results show a relatively stable temperature range throughout the year, suggesting potential benefits in electricity consumption and solar power generation. Rainfall variability exhibited a bimodal pattern, with peak values in certain months, highlighting the vulnerability of hydropower generation to rainfall fluctuations and the associated risks to infrastructure. Meanwhile, relative humidity remained relatively stable but showed a decreasing trend, with fluctuations above and below normal levels. The heavy reliance on hydropower for electricity generation in Uganda renders the country vulnerable to climatic variations, as evidenced by challenges experienced during periods of increased rainfall, such as obstruction of water flow to hydro power stations.

The findings from the current impact of climate variability on electricity consumption reveals statistically significant relationships between average temperature, rainfall, and relative humidity with domestic, commercial, and industrial electricity consumption. While temperature consistently shows a significant influence on electricity consumption across all sectors, the impact of rainfall and relative humidity appears less pronounced. In some cases, such as with industrial electricity consumption, temperature alone does not show statistically significant effects, emphasizing the importance of considering socioeconomic factors in predicting electricity demand accurately. The inclusion of GDP improved the explanatory power in predicting consumption patterns, leading to higher R-squared values compared to the model with climate variables only.

Future projections under SSP 2.6 and SSP 8.5 scenarios indicate potential deviations in temperature trends, with corresponding implications for electricity consumption patterns. The projected increase in electricity consumption, particularly in response to rising temperatures, highlights the need for proactive measures to address future energy needs and mitigate the impacts of climate variability.

However, the study is not without limitations, including the limited temporal scope and the absence of intra-annual variations in electricity consumption data. Additionally, given the complex climatic patterns in Uganda, it is possible that the electricity consumption varies from one region to another. Therefore, a region-specific study is needed to improve the analysis in order to implement tailored electricity consumption policies for effective planning and management.

5.2 Recommendations

Proposed Mitigation strategies

Diversify the energy mix by promoting the adoption of renewable energy sources such as solar, wind, and biomass to reduce reliance on hydropower and mitigate the risks associated with climate variability. Provide incentives and support for the deployment of renewable energy technologies, including subsidies, tax breaks, and capacity-building initiatives.

Implement energy efficiency and conservation measures across all sectors to reduce overall energy demand and minimize the impact of climate variability on electricity consumption. Promote energy-efficient technologies and practices in households, businesses, and industries through awareness campaigns, training programs, and financial incentives.

Proposed Adaptation strategies

Develop and implement measures to enhance the resilience of energy infrastructure, particularly hydroelectric power plants, against the impacts of climate change-induced extreme weather events such as floods and droughts. Integrate climate resilience considerations into the planning, design, and maintenance of energy infrastructure projects.

Adopt an integrated approach to water resource management that considers the interlinkages between water availability, hydropower generation, and climate variability. Implement sustainable water management practices, such as rainwater harvesting, watershed management, and efficient irrigation techniques, to enhance water security and mitigate the impacts of droughts and water scarcity on electricity production.

Strengthen institutional capacity for climate adaptation and mitigation through training programs, technical assistance, and knowledge-sharing initiatives. Foster collaboration between government agencies, research institutions, civil society organizations, and the private sector to exchange best practices, lessons learned, and innovative solutions for addressing climate-related challenges in the energy sector.

Foster active engagement and participation of local communities, indigenous peoples, and other stakeholders in the development and implementation of climate adaptation and mitigation initiatives. Empower communities to identify their vulnerability to climate change, prioritize adaptation needs, and co-design solutions that build on local knowledge, resources, and cultural practices.

Policy and Regulatory Framework

Develop and implement comprehensive climate change policies and regulatory frameworks that integrate adaptation and mitigation measures into energy sector planning and decision-making processes. Establish clear targets, timelines, and monitoring mechanisms to track progress towards climate resilience and emissions reduction goals, with periodic review and updates as needed to reflect evolving climate science and socio-economic conditions.

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APPENDIX